IAU COMMISSION 20

Positions and Motions of Minor Planets, Comets and Satellites

REPORT ON ACTIVITY 1991–1994

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I. Introduction

During the past triennium, many events related to the activity of members of Commission 20 have taken place. On the side of discovery rate and observations of asteroids, we have had an outstanding increase, as is shown in Section II of this report. The augmented rate is best noted by the record 5802 pages of the *Minor Planet Circulars* and the 20% increase of pages of the *Efemeridy Malykh Planet*.

The existing surveys of Earth-crossing asteroids, and more generally of Near-Earth Objects (*NEOs*) have resulted in an increasing discovery rate. The activity in this field is illustrated in the Report by the IAU *Working Group on Near-Earth Objects*, contained in this volume. The growing interest in these researches, in which Commission 20 is deeply involved, has led to numerous meetings, reports, and workshops. It is easy to forecast an even larger increase in the NEO search activities for the future years.

In addition, the discovery and observation of comets has seen a sharp increase. Apart from the exceptional case of comet P/Shoemaker-Levy 9 – the first observed case of an object temporarily in orbit about Jupiter, with which the fragmented comet will collide just before the next General Assembly of the IAU – 20 short-period and 23 long-period comets have been observed in the last three years. Some new objects are being discovered with unusual orbital characteristics and their classification as asteroids or comets is rather difficult.

Within the naming Committees of the Commission (*Minor Planet Names Committee* and *Comet Nomenclature Committee*) the feeling is growing that a reform of the naming procedures is necessary, in order to cope with the increasing discovery rate of minor bodies in general and the mentioned classification problems. A closer cooperation with the *Working Group on Planetary System Nomenclature*, chaired by K. Aksnes, is advisable, and is already under discussion.

The *Asteroids, Comets and Meteorites '93* meeting, held in Belgirate (Italy), June 1993, had over 400 scientists in attendance, and this testifies to a growing interest on minor bodies studies within the planetary science community. Many review papers on all aspects of minor body studies will be found in the Proceedings of the meeting, when they are published in the IAU Symposium Series.

It is sad to announce the deaths of M.A. Dirikis, R.S. Harrington, E.I. Kazimirchak-Polonskaya. With them, Commission 20 has lost some of its most active and esteemed members.

II. Minor planets (B.G. MARSDEN)

II.1 General

Commission 20 continues to be responsible for obtaining and collecting astrometric observations and for computing and disseminating orbital and ephemeris data on minor planets, principally through the media of the *Minor Planet Circulars* (*MPCs*) and the *Efemeridy Malykh Planet* (*EMP*). The *MPCs* are issued monthly by the Minor Planet Center (director B. G. Marsden, associate director G. V. Williams, contributions also from C. M. Bardwell and D. W. E. Green), Smithsonian Astrophysical Observatory, Cambridge, Mass. The *EMP* is issued annually by the Minor Planets and Comets section (chief Yu. V. Batrakov, deputy V. A. Shor, contributions also from Yu. A. Chernetenko, L. L. Filenko, G. R. Kastel', O. M. Kochetova, N. K. Sumzina, O. O. Vasil'kova and T. A. Vinogradova), Institute for Theoretical Astronomy, St. Petersburg. S. Nakano serves as the liaison between the Minor Planet Center and the numerous amateur astronomers who carry out observational and orbital work in Japan. Following the recommendation of

J. Bergeron (ed.), Reports on Astronomy, Vol. XXIIA, 185–204.

Commission 20, the FK_5/J2000.0 system was to be used in this work, and all contributing orbit computers and most contributing observers cooperated in making the change around the stipulated date of 1992 Jan. 1.

During the triennium July 1990-June 1993 a total of 5802 pages of *MPCs* were issued, the record batch in Feb. 1993 having 324 pages that had to be issued in two parts. The number of pages in the *EMP* increased from 447 in the 1991 edition to 552 in that for 1994.

The *MPCs* and the *EMP* are now available in both printed and computer form. The collected observations and the actual *MPC* pages and files containing orbital elements have been issued on diskettes since 1986, but the diskettes are being phased out in favor of an extension of the dial-in Computer Service. *STAMP*, the diskette version of the *EMP*, was initiated in 1991 and includes the possibility of extracting orbital elements for the numbered minor planets according to particular criteria (56.098.223). The complete tape of observations issued in July 1992 contained 412 043 observations of numbered minor planets and 243 630 of unnumbered minor planets, the total up 28 percent over its 1989 predecessor.

At the end of June 1993 there were 5610 numbered minor planets, a 24% increase during the triennium. The 1992 edition of the *Catalogue of Orbits of Unnumbered Minor Planets* contained 14 367 entries, up by 23% in three years. Some 3023 of these entries referred to objects observed at multiple oppositions, and the number of unnumbered objects in this category increased by as much as 19% in only one year. In order to satisfy requests for more uniform data on such objects, a *Catalogue of High-Precision Orbits of Unnumbered Minor Planets* was issued for the standard epoch 1993 Aug. 1, and there are thoughts of making this (and the accompanying diskette edition) an annual publication.

A *Dictionary of Minor Planet Names* (55.002.001) was published by L. D. Schmadel in his capacity as chairman of the Commission 20 Study Group on Minor Planet Names. Explanations are provided for all but 132 of the names assigned to 3957 of the first 5012 numbered minor planets.

II.2 Observations and Orbits

A total of 139 156 astrometric observations made of minor planets during the triennium had been published in the *Minor Planet Circulars* or included in the Minor Planet Center's accessible files by Sept. 1993. Some 35% of these observations referred to the minor planets that had by then received permanent numbers. About 25% of the numbered objects were not observed at all during the triennium, while 34% were observed ten or more times. Twelve numbered minor planets were observed at least 100 times and three more than 200 times, the latter being the Galileo targets (243) Ida and (951) Gaspra and the Apollo object (4179) Toutatis (which at a geocentric distance of 0.024 AU in Dec. 1992 was making the closest predicted approach of any natural object other than the moon), with 312, 219 and 264 observations, respectively. Provisional designations were given to as many as 13 029 unidentified minor planets observed (still often, regrettably, on only one night) during the triennium, but 20% of these objects have since been definitely identified with other minor planets, and possible identifications have been suggested for a further 2%. Three of the newly-designated minor planets, the Earth-approaching objects 1992 AC, 1992 HE and 1992 LR, were observed at least 100 times.

The 139 156 observations were obtained at 129 different observatories, of which 31 have been utilizing CCDs to perform at least some of the astrometry, while the remainder still conduct programs that are exclusively photographic. Ninety-eight observatories were responsible for 10 or more observations, 56 for 100 or more, and the following 15 observatories made more than 1000 high-quality observations:

1. European Southern Observatory (ESO), with 35 143 observations, mainly by E. W. Elst from exposures with the 1-m Schmidt and by H. Debehogne with the 0.40-m GPO astrograph; both astronomers are on the Uccle staff and make a practice of obtaining three observations of each object on a given night.

2. Palomar, with 29 864 observations, mainly by E. Bowell and others in Flagstaff on films taken by C. S. and E. M. Shoemaker and others with the 0.46-m Schmidt; this project leads in observations of numbered minor planets, although the Shoemaker program, as well as the one conducted by E. Helin with the same instrument, is designed to discover near-Earth objects, two observations generally being obtained of each object on a given night.

3. Kitt Peak, 13 440 observations by T. Gehrels, D. L. Rabinowitz and J. V. Scotti with the scanning-CCD Spacewatch camera on the Steward Observatory's 0.9-m reflector, also for the discovery of near-Earth objects, with three observations per object per night; *in addition*, there were no fewer than 70 568 single-night (triple) detections that have not been designated and inserted in the official files but that are available for checking for possible identifications.

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4. Oak Ridge, 10298 CCD observations by R. E. McCrosky and C.-Y. Shao with the 1.5-m Wyeth reflector, two observations per object per night; this is the principal program designed for follow-up rather than discovery, about one-third of the minor planets currently being numbered on the basis of observations made exclusively at Oak Ridge at their latest oppositions.

5. Tautenburg, 6552 observations by F. Börngen (sometimes in collaboration by L. D. Schmadel, Heidelberg) as a "bad weather program" with the 1.3-m Schmidt, some concentration on follow-up.

6. Kushiro, 4275 observations by S. Ueda and H. Kaneda in the leading program by amateur astronomers, using 0.25-m and 0.16-m instruments.

7. Siding Spring, 4122 observations, measurements by R. H. McNaught from plates taken with the 1.2-m U.K. Schmidt and 0.5-m Uppsala Southern Schmidt, also CCD observations with a 1.0-m reflector, concentration on near-Earth objects.

8. Crimean Astrophysical Observatory (CrAO), 3307 observations in a long-standing program conducted by N. S. Chernykh and others with the 0.4-m double astrograph.

9. Geisei, 3114 observations by amateur astronomer T. Seki, using a 0.6-m reflector.

10. Kitami, 3014 observations by K. Endate, K. Watanabe and other amateurs using 0.25-m instruments.

11. La Palma, 2528 observations, mainly of numbered minor planets with the Carlsberg Meridian Circle, under the direction of L. V. Morrison.

12. Kleť, 2434 observations with two 0.6-m instruments, under the direction through 1991 of A. Mrkos and subsequently of J. Tichá.

13. Observatoire de la Côte d'Azur, 2347 observations with the 0.9-m Schmidt at Caussols, mainly by Elst and C. Pollas photographically, development work by A. Maury to convert to a CCD search for near-Earth objects.

14. Kitakoma, 2084 observations by amateur S. Otomo with a 0.25-m reflector.

15. Haute Provence, 1098 observations, 0.6-m Schmidt, another program by Elst.

Orbital elements were computed during the triennium for a total of 9666 minor planets. The number of orbits actually computed and published was actually well over 10000, for the count refers only to the most recent results for each object. In addition, it should be noted that "Väisälä" (perihelion) orbits are automatically computed for all objects observed at least twice. Of the 9666 orbits, some 56% involved the linkage of observations at multiple oppositions or long-arc single oppositions and the need to consider planetary perturbations. In order to assist small-field observers, a special effort was made, beginning in Apr. 1993, routinely to recompute the orbits of multiple-opposition unnumbered minor planets whenever new observations are reported and to publish these results very concisely – rather than to accept that the available orbits might yield ephemerides in error by up to 5 arcmin yet delay the publication of a new orbit until enough observations are secured that the object can be numbered. The percentages of orbits computed by the nine most prolific orbit computers were: Williams 37, Bowell 19, Marsden 15, Nakano 13, Green 5 (mainly the principal share of the Palomar-Leiden T-1 survey of 1971, the astrometry for which has now been completed by I. van Houten-Groeneveld), Bardwell 3, Kaneda 2, Sumzina 1 (exclusively improvements of orbits of numbered minor planets), Filenko 1 (likewise); the remaining 4% were computed by 14 other astronomers.

Most of the multiple-opposition orbits involve the establishment of identifications by the same orbit computers, one significant success being Williams' identification of (878) Mildred, lost since its discovery on 1916, with a triplet of observations at ESO on 1991 Apr. 10 and a single CrAO observation on 1985 Nov. 11. Further images found on a 1984 Siding Spring plate and on plates taken at ESO in 1977 confirmed the identification; McNaught had in fact tentatively marked the 1984 image as a possible candidate for (878) Mildred. McNaught, and also Bowell, have made deliberate searches on isolated archival Siding Spring and Palomar survey plates for early observations of near-Earth objects; by recognizing an image of 1982 DB five months before discovery McNaught was then successfully able to recover this object, now numbered (4660) and named "Nereus", in 1990. Bowell traced (4015) 1979 VA to cometary images on the Palomar Sky Survey in 1949 that Marsden immediately noted as being P/Wilson-Harrington (1949

III), which had in fact been described as of asteroidal appearance on three other nights during its 6-day apparition; post-1979 observations show the object persistently to have asteroidal appearance, so the cometary appellation has been abandoned and the minor planet named "Wilson-Harrington".

The cometary nature of (2060) Chiron (perihelion and aphelion distances $q = 8$ AU, $Q = 19$ AU), approaching perihelion in 1996, became apparent in 1988-1989. When 1991 DA ($q = 2$ AU, $Q = 22$ AU) and 1992 AD ($q = 9$ AU, $Q = 32$ AU) were discovered – near perihelion – these objects were carefully scrutinized for cometary activity, but none was found, and the objects became (5335) Damocles and (5145) Pholus. Another object of the same general class is 1993 HA_2 ($q = 12$ AU, $Q = 38$ AU), observations of it now covering a 52-day arc. The discovery of 1992 QB_1 at a distance of more than 40 AU by D. Jewitt and J. Luu in the course of a careful search with the University of Hawaii's 2.2-m reflector for potential members of the supposed 'Kuiper Belt', in essentially stable orbits beyond Neptune, opened the possibility that this was an object in an eccentric orbit near aphelion. Nevertheless, subsequent observations indicated that 1992 QB_1 has $q = 40$ AU, $Q = 48$ AU. Its reality as a member of what must presumably be a quite populous Kuiper Belt was apparently confirmed when Jewitt and Luu discovered another object that was observed only sporadically for three months but that probably has a rather similar orbit. This second object, 1993 FW, is almost antipodal to 1992 QB_1 and was found when the search had yet to cover one square degree of sky! R. M. West, O. Hainaut and others at the European Southern Observatory contributed strongly with follow-up observations of both objects.

Bec-Borsenberger and Calaf (55.098.062, 55.098.065) have continued to provide ephemerides for the Hipparcos program and made new orbit improvements (53.098.056), as have Whipple *et al.* (54.098.054) in connection with HST. Batrakov *et al.* (54.098.038) have brought the Orel'skaya program up to date.

II.3 Theoretical Investigations

Dirikis (53.098.040) discussed the use of Väisälä orbits for searches and identifications after an interruption of observations, and Marsden (54.042.050, 56.098.226) showed how an inversion of Gauss' method generalizes the Väisälä procedure, helps in the identification process and readily produces meaningful orbits in indeterminate and uncertain cases. Shunning the use of orbital elements, Kristensen (56.098.015) described a statistical procedure to identify further single observations. Duma and Fedij (54.098.046) have considered the effect on orbit determinations of the neglect of mutual perturbations, an error in the mass of Jupiter and the difference between DE-200 and DE-202.

Goffin (54.098.035) and Williams (56.098.242) determined the mass of Ceres separately from observations of (203) Pompeja and (348) May, while Sitarski and Todorović-Juchniewicz (55.098.140) obtained a combined solution of $4.8(\pm 0.1) \times 10^{-10}$ solar mass. Schubart (56.098.002) discussed the astrometric observations used in the first mass determinations of Ceres, Pallas and Vesta; and Geffert (56.098.131) considered the mass-determination problem more generally. Landgraf (55.098.070) attempted a mass determination of (704) Interamnia from observations of (993) Moultona. Sitarski (56.098.028) used the Painlevé form to confirm the effect of relativity on the motion of (1566) Icarus, negating the need to include cometary-type nongravitational forces (53.098.013, 56.098.029).

Milani and Knežević (52.098.127, 53.098.001) extended their secular-perturbation theory to e^4 and m^2, determining proper elements and discussing secular resonances (56.098.005, 56.098.222), while Zappalà *et al.* (52.098.088, 56.098.141, 56.098.247) assessed the reliability of Hirayama families; J. Williams (55.098.145, 56.098.244) and Gordillo *et al.* (53.098.071) used clustering techniques to search for families, and Bendjoya *et al.* (54.098.047, 56.098.207) applied wavelet transform techniques. Klačka (54.098.051, 56.098.221) fully explained the Flora A jet stream as a selection effect. Froeschlé and Scholl (52.098.084), together with Morbidelli (54.098.034) and Henrard (54.042.012), have studied the secular resonances ν_5 and ν_{16}, partly in connection with the perihelion libration of (2335) James. Kozai (51.098.050) reviewed the stability of motion and secular perturbations using an averaged Hamiltonian.

Yoshikawa (51.098.049, 54.098.018) studied orbital behavior near the 5:2, 7:3 and 2:1 resonances in terms of the elliptical restricted three-body problem, showing the importance of the effect of Saturn, something Schubart (53.098.002, *Cel. Mech.* **56**, 153) has applied in the 3:2 and 2:1 cases, and Ferraz-Mello (*Cel. Mech.* in press) has considered in connection with the 3:2 resonance and depletion of the outer belt, a topic also discussed by Lecar *et al.* (55.098.144), as well as by Milani (55.098.072) in terms of "stable chaos". Tsuchida (53.098.068) determined the libration period of the 4:3 librator (279) Thule to be 190 years, with the apsides circulating in 450 years. Ipatov (51.098.044, 55.098.044, 56.098.106) and Hahn *et al.* (53.098.044) made numerical studies of motion near the 5:2 resonance, while the latter group also examined the 4:1 case (56.098.211). Hadjidemetriou (52.098.085) demonstrated a simple mapping model for the 3:1 resonance, and Ferraz-Mello (53.098.067) studied analytical results on regular solutions

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near resonances with Jupiter. Gerasimov and Mushailov (52.098.006) used the circular restricted problem to evolve orbital elements in terms of Weierstrass functions and with Vinnikov (53.098.020) made an application to the $(k+3){:}k$ resonance; they also discussed (54.098.089) Simonin's theory of the 2:1 case (108) Hecuba and (56.098.016) the effect of commensurabilities with Mars. Zagretdinov *et al.* (56.098.246) investigated the jovian 1:1 resonance, and Mikkola and Innanen (56.098.031) continued their numerical exploration of 1:1 resonances with various planets.

Zausaev and Pushkarev (53.098.016, 55.098.067, 56.098.019) integrated the orbits of Earth-approaching objects for some 11 500 years, and Zhang (53.098.110) and Hahn (53.098.061, 56.098.133) examined motions of Earth-approachers over a shorter term. Hahn and Bailey (56.098.218), as well as Steel *et al.* (56.098.238), found the eccentric orbit of (5335) Damocles to be very stable. Kuzmanoski (56.098.006, 56.098.007, 56.098.008) considered mutual encounters of minor planets. Zhang and He (52.098.126, 54.098.087) made an automatic determination of Hansen general perturbations for minor planets in the Flora group.

III. Comets (H. Rickman)

III.1 Discoveries, Recoveries and Astrometric Observations

The past triennium saw the discoveries of 23 long-period (LP) and 20 short-period (SP) comets, and 40 previously known SP comets were recovered. One of the new SP comets proved identical to the long-lost comet P/Metcalf, leading to the new double name P/Metcalf-Brewington. A drop in LP comet discoveries from the preceding triennium (from 38 to 23) is mainly due to the recent lack of space-based discoveries of Sun-grazers. All recent discoveries were Earth-based. The record number of provisional designations for a year (31 in 1989) was equalled in 1991. One of the new SP comets first received an asteroidal provisional designation (1990 UL3 = 1990 XVI P/Shoemaker-Levy 2).

The distinction between amateur and professional contributions to comet discoveries and recoveries is becoming less clearcut than before. Counting only work done at observatories affiliated to universities, academies or other national scientific institutions as "professional", the discoveries of LP comets continued to have a 1/3 contribution by amateurs, mostly visually at magnitudes 8–11. The 2/3 share of professional discoveries were photographic at magnitudes 15–18 with one exception – a CCD-aided discovery by the Spacewatch team. This and a SP comet discovery at magnitude 21 by the same team represent the introduction of CCD technique in comet discoveries.

The 19 remaining SP comets fall into two categories: three visual discoveries at magnitudes 8–10 by amateurs (P/Metcalf-Brewington, P/Levy and P/Brewington) and 16 photographic discoveries, mostly at Palomar (14 cases), where the magnitudes range from 13 to 18. Most remarkably, at Palomar, the Shoemaker-Levy team discovered nine SP comets (P/Shoemaker-Levy 1 – 9), which by far exceeds the number of SP comets ascribed to any previous discoverers. C.S. Shoemaker has now discovered 30 comets, thus rivalling J.-L. Pons as the all-time top comet discoverer. With large contributions also from the PCAS (Planet-Crossing Asteroid Survey) led by E. Helin (4 LP comets and 1 SP comet), and the Palomar Sky Survey II with comets searched for by J. Mueller (3 LP comets and 3 SP comets), this places nearly 60% of all recent comet discoveries at Palomar Observatory. The second most important discovery site was Siding Spring with 4 cases (9%). The latter constitutes the majority (2/3) of all Southern hemisphere discoveries.

Recoveries of SP comets continued to be done mainly with CCD detectors, the outstanding contribution coming from the Spacewatch team at Kitt Peak (J. Scotti: 17 recoveries + 2 shared with other observers). However, while the total number of CCD recoveries during the past triennium was nearly the same as previously, the number of photographic recoveries had a dramatic increase mainly due to T. Seki (11 recoveries). In total there were 22 CCD recoveries (at magnitudes 18–22) and 15 photographic ones (at magnitudes 14–20) plus one shared between the two techniques. In addition, two remarkable SP comets were recovered visually at 11th magnitude: 1991t P/Hartley 2 and 1992t P/Swift-Tuttle. In 28 cases the recovery circumstances can be compared with earlier ephemeris-aided recoveries, and nearly half of these occurred at larger pre-perihelion distances than ever before, e.g. P/Ashbrook-Jackson (4.7 AU), P/Tuttle (6.3 AU) and P/Tempel 1 (3.9 AU). The median heliocentric distance for the 35 pre-perihelion recoveries was [illegible]6 AU with quartiles at 2.0 and 3.8 AU. There is a clear trend toward more frequent near-aphelion observations of SP comets, of which there were four during the past triennium. The current total number of annual comets is thus 11 (P/Encke, P/Grigg-Skjellerup, P/Machholz, P/Tempel 2, P/Schwassmann-Wachmann 2, P/Arend-Rigaux, P/Gunn, P/Helin-Roman-Crockett, P/Smirnova-Chernykh, P/Helin-Roman-Alu 1 and P/Schwassmann-Wachmann 1), indicating that the identification of recovery observations is becoming less meaningful.

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At the General Assembly in Buenos Aires in 1991, B.G. Marsden reminded Comm. 20 attendees of his 1973 prediction that P/Swift-Tuttle, the parent of the Perseid meteors, might return in late 1992. Two weeks later, an impressive display of Perseids within 0.1 day of the Earth's passage through the plane of the comet's current orbit suggested that the comet was nearby. Despite this, little in the way of professional searches were made for the comet, and it was finally found already at magnitude 11 in late September 1992 by the Japanese amateur T. Kiuchi (IAUC 5620). The predicted perihelion time proved to be only 17 days in error after 130 years (the longest period of any comet the return of which has been successfully predicted -- the record hitherto having been held by P/Halley). Subsequently, L. Kohoutek found an image of the comet on a single plate taken at Calar Alto in January 1992. This observation confirmed other pre-recovery observations then by Italian amateurs. The accuracy of the final predicted perihelion time is remarkable, when one considers that the Cape observations in October 1862 show large systematic residuals, smaller systematic effects also being noticeable in July 1862 and the January 1992 pre-recovery. The accuracy becomes astounding when one appreciates that an entirely gravitational orbit solution satisfies the general character of the comet's motion via 1737 back to the years +188 and -68 (Waddington, IAUC 5671). In a suggestion that was widely misunderstood, and before the +188 and -68 identifications were established, Marsden hinted that there was a tiny chance that P/Swift-Tuttle could collide with the Earth in 2126 and suggested that the problem posed by the October 1862 discordance could be resolved by making a series of observations of the comet with large telescopes in the southern hemisphere between mid-1993 and the end of the century.

Eleven comets were observed on their critical, second apparitions in addition to 1991a P/Metcalf-Brewington and 1992t P/Swift-Tuttle. Nine of these have orbital periods from 6 to 15 yrs and were discovered on their previous apparitions; for the two remaining ones (P/Schuster and P/Kowal 2), one intervening apparition had been missed. The latter was recovered by M. Ishikawa at a position yielding a large perihelion correction: $\Delta T = -54^{\mathrm{d}}$. SP comets missed at expected perihelia were: P/Tritton in 1990; P/Russell 1, P/Haneda-Campos and P/Kowal-Mrkos in 1991; P/Shoemaker 2 and P/du Toit-Hartley in 1992; and P/Wiseman-Skiff and P/Lovas 2 in 1993. Most of them were badly placed for observation, and the last two had their perihelion passages only in June 1993; in addition, P/Kowal-Mrkos has undergone strong jovian perturbations and now has a too uncertain orbit to hope for recovery.

Observations of remote comets continued to be done mainly by K. Meech (summary in ADC, p. 12) including comets 1983 XII Černis at more than 19 AU and 1985 XII Shoemaker at 17 AU. Hainaut *et al.* (ADC, p. 54) reported on the last observation, at the detection limit, of 1986 III P/Halley at 16.2 AU and on negative results from searching for other comets at 17–32 AU. The possibility of detection of several very distant comets was also suggested by Bailey *et al.* (55.103.015). Observations of the P/Halley outburst in Dec. 1990 at 14 AU were described and interpreted by West *et al.* (53.103.106), Sekanina *et al.* (56.103.166) and Meech (55.103.120). Remote observations of P/Halley were reviewed by Boehnhardt (ADC, p. 3).

Astrometric observations were routinely published in the *MPC*'s, and the number during the past triennium was 7831, whereof 3279 referred to LP comets and 4552 to SP comets. The largest sets of observations were acquired for P/Swift-Tuttle (718), P/Schaumasse (479) and 1991 XXIV Shoemaker-Levy (419). Of the 110 observatories involved, more than 30 are using CCDs at least part of the time. The most prolific ones were Oizumi (1088 observations; however, generally involving dozens of observations of the same comet during each night), Oak Ridge (834), Spacewatch (530), Geisei (505), Chiyoda (424), Linz (385), Palomar (374) and Kleť (316). The 1st, 4th, 5th and 6th in this list are amateur observatories with small-field instruments. The Spacewatch programme was described by Gehrels (54.013.094), and accounts of observations made at Skalnaté Pleso were published by Svoreň (53.103.016; 56.103.014).

III.2 Orbits and Ephemerides; Orbital Evolution

New editions, the seventh and the eighth, of B.G. Marsden's Catalogue of Cometary Orbits were issued in 1992 and 1993, the seventh partially typeset, the eighth completely so. G.V. Williams co-authored these editions. The eighth edition contained orbits for 1397 apparitions of 855 comets, 174 of short period (of which 107 have been observed at more than one perihelion passages). 'Original' and 'future' orbits were given for 289 comets with high-quality orbit determinations. The *Comet Handbook*, edited by S. Nakano and D.W.E. Green, was published yearly by the *ICQ*, containing orbits and ephemerides for upcoming cometary apparitions. Yeomans and Wimberly (53.103.023) presented data for all SP comet apparitions expected in 1990–2010, and Kosai and Nakamura (53.103.024) made a statistical analysis of discovery/recovery conditions.

On the basis of Kresák and Kresáková's (54.103.011) analysis of the prospects for identification of old apparitions of known SP comets, Carusi *et al.* (54.103.067) were able to identify La Hire's comet of 1678

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with P/d'Arrest. This accomplishment is remarkable for a comet with a relatively strong nongravitational effect and repeated encounters with Jupiter, but equally striking is the fact that the best fit requires the nongravitational perihelion delay of P/d'Arrest to have remained practically constant over three centuries.

Comet 1993e (P/Shoemaker-Levy 9), discovered some 4° from Jupiter by C.S. and E.M. Shoemaker and D.H. Levy, as well as independently by others, was remarkable in that it was seen to consist of from 11 to 20 separate nuclei over a 50" line. Evidently the comet had brightened because of the splitting, and the splitting had been brought about by a passage within Jupiter's Roche limit. From its present distance from Jupiter and the failure of observers to detect the comet at its opposition in early 1992, Marsden immediately suggested a Jupiter encounter in July 1992 (IAUC 5726), the nominal date being found in error by only 20 days when there were sufficient observations to refine the orbit computation. He then suggested that the comet was at least temporarily a satellite of Jupiter (IAUC 5744). By the end of April, computations by Marsden and independently by Nakano were refining the circumstances of the 1992 encounter and indicating that a 1994 encounter might even be closer. On May 22 (IAUC 5800) Marsden announced the likelihood that the center of the comet train would actually collide with Jupiter in July 1992, and A. Carusi (IAUC 5807) noted that, if there were a reasonably central collision, all of the nuclear train would collide with Jupiter, even if it were 30 times its observed length.

A new look at the problem of interstellar (hyperbolic) comets was taken by Kresák (55.103.021), who concluded that no positive evidence for such orbits exists, devoting special analysis to comet 1976 I Sato (55.103.044). Yabushita (53.103.014) had estimated the maximum nongravitational shift of $(1/a)_{\text{orig}}$ and found comet Sato to be possibly interstellar. By contrast, Matese *et al.* (54.102.027; 56.102.089) found that negative $(1/a)_{\text{orig}}$ correlates with small perihelion distance and retrograde orbit and offerred a possible explanation in terms of abnormally large nongravitational effects.

Todorović-Juchniewicz (56.103.005) determined original and future orbits of ten LP comets. Nongravitational orbit determinations were reviewed by Yeomans (53.102.045), and Sitarski (53.102.043) reviewed the problem of long-term linkages. Many attempts were made to model nongravitational effects in terms of physical parameters of the nuclei rather than using the standard (A_1, A_2, A_3) parameters. Sitarski (52.102.068) introduced a scheme involving the spin of the nucleus, applying it to P/Kopff, and then went on to study P/Grigg-Skjellerup (54.103.075; 55.103.102), P/Metcalf-Brewington (55.103.150), P/Swift-Gehrels (Bielicki and Sitarski 54.103.155), P/Kearns-Kwee and P/Gunn (Todorović-Juchniewicz and Sitarski 56.103.078). Szutowicz (56.103.247) similarly studied comet P/Wolf-Harrington. Very complex models also involving the light shift (displacement of the photocenter from the center of mass) as a physical parameter were discussed by Medvedev (54.102.013) and applied to P/Halley by Batrakov and Medvedev (52.103.161). Chernetenko (52.103.120; 54.103.068) applied such models to orbital linkages of comet P/Encke.

Investigations of the motion of P/Halley over its observed millennia were reviewed by Yeomans (53.103.155) and Ziołkowski (53.103.156), and the identification of ancient observations was discussed by Stephenson (53.103.154). The secular perturbations suffered by this comet over 10^5 yrs were investigated by Obrubov (56.104.070; MPB, p. 69). Numerical integrations of the orbital evolution of "giant comet" Chiron were performed by Hahn and Bailey (52.102.028), demonstrating that past visits into Earth-crossing orbits of the Jupiter family type are statistically likely. The temporary jovian satellite capture of P/Helin-Roman-Crockett shortly preceding its discovery was investigated by Tancredi *et al.* (52.103.187). Chaos in the long-term motions of comets P/Slaughter-Burnham (56.103.226) and P/Boethin (MPB, p. 97) was studied by Benest and Gonczi by estimating Lyapunov Characteristic Exponents.

III.3 Cometary Origin, Dynamics and Spatial Distribution

General reviews are found in the proceedings of IAU Coll. 116 and IAU Symp. 152 as well as in "Physics and Chemistry of Comets" (ed. W.F. Huebner; Springer-Verlag 1991). Among specific topics the most intense scrutiny was devoted to the dynamical evolution of the Oort cloud and the modelling of cometary capture.

The picture of Marochnik *et al.*, revisited in (55.102.053), of a massive Oort cloud whose angular momentum is too large for formation by means of gravitational scattering from the outer planets was criticized by Weissman (53.102.012) on the ground that the angular momentum of the cloud should be mostly acquired by the action of external perturbers. Later on, Lopatnikov *et al.* (54.102.020) modelled the "thermalization" of initially flat swarms of comets, concluding that the angular momentum of a swarm formed at the periphery of the solar nebula is little affected by such perturbations. Simulations of the long-term Oort cloud evolution predicting the influx rate into the inner Solar System were performed by Heisler (52.102.033), Matese and Whitman (56.102.033) and Chakrabarti (56.102.023). Brunini (*A&A*, **273**, 684,

1993) investigated the dynamical friction effects on the Oort cloud due to the solar motion by analytical means and concluded, in agreement with an earlier suggestion by Brunini and Canosa (55.103.019), that otherwise unexplained features of the aphelion distribution of new comets can be thus accounted for. The effects of deeply penetrating stellar encounters on the Oort cloud population and on the injection of comet showers were calculated by Weissman (56.102.049); see also Fernández (55.102.017). Possible associations of LP comets, earlier suggested by Biermann and coworkers to result from individual passing stars, were discussed by Whipple (53.102.081).

The flux of near-parabolic comets passing perihelia in the outer planetary zone was modelled by Yabushita and Tsujii (53.102.005; 54.102.026), thus evaluating the rate of captures into short-period orbits. This capture rate and its failure to balance the estimated loss rate of the Jupiter family was discussed by Rickman (52.102.040; 56.103.041). Further discussion of the origin of SP comets was given by Guliev (56.102.001). The choice between alternative sources of SP comets, supplementing the classical Oort cloud, was discussed by Levison (56.102.086) and Bailey (56.102.035). The transfer from the Kuiper belt was investigated using Markov chain modelling by Levison (54.091.024; 55.102.020), and using new efficient integrators to trace the orbits over 10^9 yrs by Levison and Duncan (*ApJ*, **406**, L35, 1993) and 10^8 yrs by Holman and Wisdom (*AJ*, **105**, 1987, 1993). Captures from the Oort cloud into Halley-type orbits were simulated by Gallardo and Fernández (PC, p. 35). Mapping techniques to model cometary chaos were reviewed by Froeschlé (55.042.053; 55.042.099). Manara and Valsecchi (54.102.011; 56.042.069) and Valsecchi (PC, p. 81) studied orbital transformations due to close encounters with the outer planets for comets in orbits of low or moderate eccentricities by accurate integration and found the speed-up technique of increasing the planetary masses to distort the perturbation distributions. Valtonen *et al.* (56.102.034) used numerical experiments with close encounters to find analytic formulae for the perturbation distributions. Emel'yanenko (52.102.035; 54.102.024; 55.102.046) developed an analytical theory for weak perturbations of cometary orbits in the circular restricted three-body problem and applied this (56.042.037; 56.102.013; 56.102.018) to study the orbital diffusion of LP comets.

Long-term integration samples based on real SP comets by Nakamura and Yoshikawa (53.102.084; 53.102.088; 56.102.037) and Tancredi and Rickman (55.102.019) gave indications of the statistics of jovian perturbations and the expected perihelion distance distribution of the Jupiter family. Lindgren (56.102.088) used a random sample of starting orbits for such integrations to find the typical dynamical residence time in the observable Jupiter family. Rickman *et al.* (SP, p. 55) performed Monte Carlo simulations of the physico-dynamical evolution of such comets, and Fernández *et al.* (SP, p. 143) investigated observational indications of their perihelion distance distribution. Evidence relevant to the physical evolution was found from statistics of nongravitational effects by Rickman *et al.* (54.102.018), indicating temporary, short-lived activation of SP comets after major reductions of the perihelion distance. Attention was focussed on Sun-grazing, or even sun-plunging, orbits as a relatively common cometary end state by Bailey *et al.* (55.102.010), mainly effective for LP and Halley-type comets.

The origin of comets by collisional aggregation in the transplutonian region was studied by Safronov and Gussejnov (52.102.015), and the dynamical criteria for the capture of the Oort cloud from a common cometary population of the stellar association where the Sun was formed were evaluated by Zheng *et al.* (52.102.070). Negative results from searches for the Kuiper belt were published by Levison and Duncan (52.102.014) and Cochran *et al.* (55.102.027), while the first positive detections may have been made by Jewitt and Luu (*Nature*, **362**, 730, 1993; see Sect. II.2). A search for comets in the vicinity of Jupiter was described by Tancredi and Lindgren (56.102.077; 56.103.081).

IV. Satellites (J.-E. Arlot)

IV.1 Observations for astrometric purposes – Photometry

At the USNO in Washington D.C., photographic observations of the Galilean satellites of Jupiter, satellites I-VIII of Saturn and the Martian satellites were continued by D. Pascu with the 63-cm refractor. This brings to 20 the number of apparitions observed for the Galilean satellites, 19 for Saturn's system and 12 for the satellites of Mars. Positions for Saturn's satellites are available only from 1974 to 1980. Positions for the Galilean satellites are available for 1967/68 as a result of the McCormick refractor and 1973-1993 as a result of the USNO 63-cm. Positions for the Martian satellites are available for 1967, some for 1969, 1971 and all from 1982 - 1988. Some of the Martian satellite observations were made with the 1.5-m Astrometric Reflector. The Galilean satellite observations are sent to JPL in support of the GALILEO project, and to the Bureau des Longitudes in Paris in support of ephemeris development. In addition to the photographic program for the brighter satellites, CCD observations are made of seven faint inner satellites: JV, JXIV, SXII, SXIII, SXIV, UV and NII (Rohde *et al.*, *BAAS*, **25**, 1993 ; Pascu *et al.*, *BAAS*, **24**, 1059, 1992). These observations have been continued for 12 years with the 1.5-m Astrometric reflector at Flagstaff by Pascu, P.K. Seidelman and J.R. Rohde. These observations provide both astrometric and photometric data (Pascu *et al.*, *BAAS*, **22**, 1117, 1990 ; Pascu *et al.*, *Icarus*, **98**, 38, 1992).

Astrometric positions of satellites Jupiter VI and VII were obtained on plates taken at Table Mountain Observatory in 1968 and are published by J.D. Mulholland (*PASP*, **102**, 1328, 1990). Shelus *et al.* obtained positions of Jupiter VI through Jupiter XIII at McDonald Observatory (53.099.006) as did Whipple *et al.* (55.099.015,105).

At JPL, R.A. Jacobson analyzed observations acquired from the Voyager missions to Uranus and Neptune. The results of these analyses were revised sets of dynamical constants, e.g., planet and satellites masses, for both the Uranian and Neptunian systems and numerically integrated ephemerides for the satellites. In addition, he converted the Voyager satellite observations to an equivalent astrometric form for general use (Jacobson *et al.*, 54.101.007 ; Jacobson, 54.101.003 ; Jacobson, *A&ASS*, **96**, 549,1992). From Voyager images, Showalter detected 1981 S 13 (Saturn XVIII) and studied its role in Encke gap (53.100.015).

T. Nakamura reported observations of close approaches between the Galilean satellites (Nakamura *et al.*, Proceedings of IAU Colloquium 127, "Reference Systems", p319, 1991) and published astrometric observations of the central satellites of Jupiter during 1986-1990 (Nakamura *et al.*, 53.99.001).

D.B. Taylor from the RGO reported CCD observations of the major satellites of Saturn, Uranus and Neptune that were made using the 1-m Jacobus Kapteyn Telescope on La Palma, Canary Islands during the 1990 and 1991 oppositions. Williams *et al.* (*MNRAS*, **250**, 1, 1991) used the 1990 CCD data for Nereid together with comparisons stars to estimate the period of rotation of Nereid. Beurle *et al.* (1993) have made a preliminary reduction of the Saturn satellite data for the 1991 opposition. They have shown these observations to be comparable in quality to the best photographic observations.

R. Viera-Martins reported that, using the Brazilian 1.6-m reflector, 668 CCD images of the Uranus system and 622 CCD images of the Neptune system were made and are now being reduced. A new photometric technique for the reduction of natural satellite images near a bright planet was also developed at the Observatorio Nacional (Rio de Janeiro, Brazil). These methods were applied to 173 photographic plates of the Uranium system. The results are presented in the Ph. D. dissertation of C.H. Veiga.

At Bordeaux Observatory (France) a CCD camera was built and used for the observation of the mutual events of the Galilean Satellites as well as for the astrometric measurements of positions of the satellites of Saturn.

At the Bureau des Longitudes (France), a campaign of CCD astrometric observations was continued and some data were published concerning the satellites of Mars (Colas and Arlot, 54.097.037 ; Colas, *A&ASS*, **96**, 485, 1992). and the satellites of Neptune (Colas and Buil, *A&A*, **262**, L13,1992).

At the Pulkovo Observatory, St. Petersburg, regular observations of the Galilean satellites with the 65-cm astrograph and the normal 33-cm astrograph were continued. 53 plates with satellites were taken altogether, but not yet processed. Moreover, the Saturn's satellites S2-S5 and S8, the satellites of Uranus U1-U4 and Neptune 1 were observed at the Byurakan Observatory by the staff members of Pulkovo Observatory using the 2.6-m reflector. 153 positions of Saturn's satellites with respect to Titan, 44 positions of Uranus' satellites with respect to the planet and 9 positions of Neptune 1 with respect to Neptune have been obtained. The mean error on the positions varies from 0.34" to 0.56". The results have been submitted for publication. 8 positions of Deimos in November 1990 were recorded and processed. A number of positions of Phobos and Deimos, observed in 1988, were also published (6.51.154, 6.51.155, 6.51.156).

S.V. Tolbin has published the observations of Saturn's satellites S1-S6 and S8 (220 plates), taken in 1977-1982 with the 65-cm refractor (11.51.102). The coordinates of the satellites were compared with modern theories. The mean residuals, equal to 0.20", is a sign of the high quality of these observations. Toblin published also the results of photographic observations of the Saturn's system (159 plates) taken at Pulkovo with the normal astrograph (11.51.103). The mean residuals for these observations (S2-S6, S8) are of 0.30".

At Goloseevo Observatory, Ukraine, the photographic observations made in preceding years were processed. The results of observations of Jupiter 6 at Goloseevo and at Maidanak observatories in 1987-1988 (12 positions) have been published (53.099.017, 54.099.039). The results of observations of the outer satellites of Jupiter in 1987-1989 at Majdanak (22 positions of Jupiter 6, 4 positions of Jupiter 7, and 2 positions of Jupiter 8) have been submitted for publication.

The observations of Saturn's satellites made at Goloseevo in 1980 with two instruments (the 40-cm double astrograph, and the 40-cm double large field astrograph) have been processed and published

(4.51.93) (altogether 305 positions of S1-S8), as well as the results of observations of S2-S9 taken in 1990 at Majdanak with the 60-cm reflector (altogether 232 positions). Also the results of observations of the satellites of Uranus and Neptune, including 13 positions of Triton made in 1990 at Majdanak, were deposited.

At Sternberg Astronomical Institute (SAI), Moscow, a new reduction of plates with Phobos and Deimos taken in 1988 at Majdanak by staff members of SAI (660 positions of Phobos and 639 positions of Deimos, referred to FK5/J2000.0) has been undertaken. The new positions have been compared with the theory of motion of the satellites, developed at the Space Flight Control Center (*Astronomicheskij Zhurnal*, **18**, 815-818, 1992).

At Nikolajev Observatory, Ukraine, 42 plates of the Galilean satellites and 42 plates with the bright Saturn's satellites (S3-S5, S8) were taken using the zone astrograph (D=210, F=74 cm). The observed positions with respect to the FOKAT catalogue have been processed and the results were deposited. The results of observations of these satellites in 1987-1987 were also deposited (11.51.99).

At Abastumani Observatory ,Georgia, observations of the satellites of Jupiter, Saturn, Uranus and Neptune with the large field astrograph (D=40cm, F=300cm) were continued. More than 100 plates with the Galilean satellites, more than 200 plates with Saturn's satellites (S3-S6, S8), more than 200 plates with Uranus 3 and Uranus 4, and more than 200 plates with Neptune 1 have been taken. A preliminary analysis of the results has been made. Mean errors of the positions, with respect to stars of the FOKAT-S catalogue, vary between 0.2" and 0.3".

The group of scientists involved in the Phobos-2 mission has published the list of on-board astrometric observations of Phobos and Deimos and other relevant data (53.097.140).

Nicholson *et al.* (52.100.031) and Hamilton *et al.* (54.100.037) reported observations of the co-orbital satellites of Saturn (52.100.031).

In 1991, an important campaign of observation of the mutual events of the Galilean satellites took place. Predictions were made by Aksnes and Franklin (*Icarus*, **84**, 542, 1990), by the British Astronomical Association in London (52.099.042) and by Arlot (*A&A*, **237**, 259, 1990). Some observations were published (Souchay *et al.*, *A&A*, **264**, 314, 1992; Le Campion *et al.*, *A&A*, **266**, 568, 1992; Mallama, *Icarus*, **97**, 298, 1992 and *Icarus*, **95**, 309, 1992; Oprescu *et al.*, *Rom. Astr. J.*, **2**, 61, 1992; Allen *et al.*, *Earth Moon and Planets*, **58**, 105, 1992; Froeschlé *et al.*, *A&A*, 1992). Descamps *et al.*, (*Icarus*, **100**, 235, 1992) put also into evidence the positions of hot spots on Io, the first satellite of Jupiter. At the same time, some results of the former campaign made in 1985 were also published (Arlot *et al.*, *A&ASS*, **80**, 1, 1990; Arlot *et al.*, 55.099.027; Franklin *et al.*, *AJ*, **102**, 806, 1991; Vasundhara, *J. Astrophys. Astr.*, *12*, **69**, 1991).

Blanco *et al.* (53.101.015) and Buie *et al.* (55.101.090) reported the observation of mutual events in the Pluto/Charon system.

IV.2 Comparison of observations with theories – Determination of elements

At JPL, the masses of Uranus and its satellites were determined using the recent Voyager data (Jacobson *et al.*, Meeting of the AAS, Division on Dynamical Astronomy, Key Biscayne, Fla, 1991; Jacobson *et al.*, paper G 32A-3, Spring Meeting of the AGU, Montreal, Canada, 1992 ; Jacobson *et al.*, 55.101.016). At RGO, in cooperation with Bordeau Observatory, Taylor *et al.* (*A&A*, **249**, 569, 1991) have analysed meridian circle observations of Titan and Iapetus made with the Carlsberg Automatic Meridian Circle on La Palma and the Meridian Circle at Bordeaux. From their analysis the corrections to the position of Saturn from the DE200 ephemeris agree well with the latest ephemeris DE202. The only significant correction to the elements of the satellites is to the mean longitudes of Iapetus. Harper and Taylor (*A&A*, **268**, 326, 1993) have determinded new improved orbital elements for the major satellites of Saturn from an analysis of observations spanning the period 1874 to 1988. New masses for the satellites Mimas, Enceladus, Tethys and Dione were derived. At USNO, an analysis of photographic astrometric observations of the Galilean Satellites was presented (55.101.091). At Bordeaux Observatory (France) Dourneau (*A&A*, **267**, 292, 1993) presented a theoretical work and fit the orbital elements of the eight major satellites of Saturn to 100 years of observations. At the Bureau des Longitudes, M. Chapront-Touze calculated the orbits of the Martian satellites from her theories (*A&A*, **240**, 159, 1990). From Voyager 2 data, Owen *et al.* (53.101.004) prsented the orbits of the six new satellites of Neptune. An analysis of the Pluto/Charon mutual events was made by Marcialis (52.101.043) and by Tholen and Buie (52.101.111).

N.V. Emel'yanov and S.N. Vashkov'yak (Sternberg Astronomical Institute, Moscow) have finished working on the determination of the dynamical and kinematic characteristics of the Martian satellite system from all available ground- and space-based observations. Among the determined parameters, are

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included the elements of Phobos and Deimos, the velocities of secular motions of angular elements, the secular accelerations of the satellites, the mass of the planet and the J2, J3, and J4 harmonics of its gravitational field, the position (coordinates) of the north pole of Mars' rotation axis. Using the absolute positions (w.r.t. reference stars) of Phobos and Deimos, the systematic differences between the dynamical system adopted in the DE118 ephemeris and the FK4 system were determined. The results are published in *A&A*, **267**, 634-642 (1993).

V.A. Shor (ITA, St.Petersburg) has published an improvement of the orbital parameters of Phobos and Deimos taking into account Phobos-2 on-board observations as well as all other available ground- and space-based observations of the satellites. The theoretical model used in that work was previously developed according to the analytical theory by Sinclair. Secular accelerations of both satellites were derived, with good precision, in agreement with the results of other investigators (54.097.011).

N.O. Kirsanov (ITA, St.Petersburg) has compared 473 positions of Titan and 93 positions of Hyperion, covering the time interval from 1972 to 1984, with the results of numerical integrations. The differential correction of initial elements of the two satellites has been fulfilled. The new orbits agree with the used observations with a mean error of 0.36". The work is aimed at the construction of a semi-analytical theory of the satellites, which is now under development.

I.A. Gerasimov (Sternberg Astronomical Institute) and B.R. Mushailov have studied the evolution of Hyperion's orbit (53.100.004, 53.100.020).

S.A. Gasanov (Sternberg Astronomical Institute) has used 314 observations of Iapetus, covering the time span from 1974 to 1984, to improve the parameters of the analytical theory of the satellite constructed with the Laplace method (54.100.010, 54.100.017). The observations are represented with a mean error of 0.73".

N.N. Gor'kavyj (Astronomical Institute, Moscow) and co-authors were involved in the elaboration of the theory of Neptunian arcs (54.101.126, 54.101.127, 55.101.007, 55.101.008, 55.101.009).

IV.3 Theoretical studies

Concerning the Galilean Satellites, the orbital resonance among JI, JII and JIII was studied by Changyin and Lin (54.099.056). At Lille University (France), Duriez and Vienne built a new theory of the eight major satellites of Saturn where all the dynamical parameters are taken into account at the same time (Duriez and Vienne, 53.100.006; Vienne and Duriez 53.100.014; Vienne and Duriez 55.100.009). A study of the secular acceleration of Mimas was presented (Vienne *et al.*, 55.042.043) and a synthetic theory of the motion for Titan-Hyperion was studied (Duriez, 55.042.041). Gerasimov and Mushailov studied the evolution of Hyperion's orbit (53.100.004,020) and an analytical theory of the motion of Iapetus was presented by Gasanov (54.100.017). Sessin made theoretical studies of the Mimas-Tethys system (55.042.044) and the influence of Enceladus in the motion of Helene was studied by Bevilacqua and Sessin (55.042.045). M. Chapront-Touze completed a theory of the motion of Phobos and Deimos (*A&A*, **235**, 447, 1990), Ivanov *et al.* (52.097.031) published a new theory of the motion of Phobos and Vashkov'yak and Emel'yamov (52.097.027) improved Phobos' orbit. Wnuk and Breiter also published a study on the motion of satellites in Mars' gravity field (53.097.200). Krasil Nikov (52.042.027) studied the spatial rotations of a satellite about the mass center in the circular 3-body problem in the case of a main resonance. Secular perturbations of fictitious satellites of Uranus were studied by Kinoshita and Nakai (54.042.092) and a semi-analytical theory for the motion of Uranus' satellites was presented by Lazzaro (54.101.012). At OCA (France) Oberti published an analytical model for an accurate solution for Nereid's motion (52.101.013).

IV.4 Ephemerides – Numerical Integrations – Predictions of events

At JPL, R.A. Jacobson began the development of numerically integrated Galilean and Saturnian satellite ephemerides in support of JPL's Galileo, and Cassini missions, respectively (Jacobson *et al.*, meeting of the AAS, Division on Dynamical Astronomy, Santa Barbara, Ca, 1993). Other activities included maintaining and updating the satellite observations database and providing ephemerides for a number of JPL and non-JPL users. Among the former were the JPL Mars Observer project (Phobos and Deimos) and the Pluto Fast Fly-by pre-project (Charon). Among the latter were the Space Telescope Science Institute (all natural satellites). At RGO, using the numerical integration of Hyperion by Sinclair and Taylor (1985), Taylor (*A&A*, **265**, 825, 1992) has developed a synthetic theory for the motion of this satellite and fitted it to the modern photographic observations. The coefficients of the synthetic long-period theory were used by Message (1993) as starting conditions in his differential correction procedure (based on a new theory of the long-period motion) to determine a set of dynamically consistent coefficients. A study of Saturnian satellite ephemeris calculations was presented by Rongchuan and Kaixian (54.100.035).

Data on the mutual events and eclipses by Saturn will help refine the motions of the Saturnian satellites. Preliminary predictions were made by Sema (*A&A*, **265**, L21, 1992) for eclipses of Iapetus and by Thuillot *et al.* (*BAAS*, **24**, 938, 1992) for the eclipses and mutual events.

IV.5 Dynamics of the Ring Systems

Goldreich (55.042.024) outlined some of the main processes that shape the planetary rings, and three-dimensional perturbations in a narrow planetary ring were studied by Kolvoord and Burns (55.091.005). A theory of the Neptunian ring arcs was made by Gor'kavyj *et al.* (54.101.126,127) and an explanation of those arcs was also given by Porco (54.101.005). Concerning the rings of Uranus, papers "Shepherding Satellites and Dynamical Structure of the rings of Uranus" were published by Kozai (*PASJ*, **44**, 135, 1992 and *PASJ*, **45**, 263, 1993). Colwell and Esposito have published a numerical model of Uranian rings (52.101.003). A paper on the orbits of shepherd satellites deduced from the structure of the rings of Uranus was also published by Murray and Thomson (52.101.025). French *et al.* presented a work on the dynamics and structure of uranian rings (54.101.104). Concerning the rings of Saturn, Kolvoord and Burns published a collisional modelling of Saturn's F ring (52.100.030) and the dynamics of Saturn's E ring particles was also published (55.100.069). Concerning observations, several efforts were completed: Turtle *et al.* (52.100.026) deduced the kinematics of Saturn's major narrow rings from Voyager data and ground-based observations and Nicholson *et al.* (52.101.011) reported on the observation of Neptune's ring arcs by stellar occultation as well as Sicardy *et al.* for the 1983-1989 period (53.101.006).

V. Radar Astrometry for Asteroids, Comets, and Natural Satellites (D.K. YEOMANS)

Radar observations of the solar system's small bodies began with observations of asteroid (1566) Icarus in June 1968 and since that time there have been successful radar experiments involving over 60 different main belt and near-Earth asteroids. Although the focus of these radar experiments has been to infer the asteroids' physical characteristics from the strengths and properties of the returned signals, corrections to the predicted Doppler and time delay ephemerides are also possible. Once these corrections are made, Yeomans *et al.* (*AJ*, 94:189) showed that the resulting differences between received and transmitted frequencies (Doppler shifts) and the round trip time delays can provide extremely powerful data types for the orbit determination of asteroids and comets.

Astrometric radar data effectively measures the object's distance and velocity along the observer's line-of-sight and hence these data are complementary to optical, plane-of-sky measurements. Radar data taken during an object's close approach to the Earth are most powerful, and the orbit refinement most dramatic, if the object has only a short optical astrometric history.

In orbital solutions, radar observation residuals for near-Earth objects are often less than 1 Hz in Doppler and less than a microsecond in round-trip delay time. At the Arecibo transmitter S-band frequency (2380 MHz), these residuals correspond to range and velocity errors of less than 150 m and less than 6.5 cm/sec. For the Goldstone X-band frequency (8510 MHz), the corresponding velocity error is less than 2 cm/s. The power of the radar data becomes evident when one realizes that radar measurement errors are orders of magnitude smaller than the position and velocity uncertainties inherent in orbits based only upon optical data over short time intervals.

Although astrometric radar data have been published since the first asteroid radar experiment in 1968, few of these measurements have been used to improve asteroid orbits. Lieske and Null (*AJ*, **74**, 297) included the 1968 Goldstone radar data in their early analysis of the orbit of (1566) Icarus but it was more than two decades before additional "radar" orbits were published by S.J. Ostro and colleagues for close Earth approaching asteroids 1986 JK (*Icarus*, **78**, 382), 1989 PB (*Science*, **248**, 1523), (1627) Ivar (*AJ*, **99**, 2012), and 1986 DA (*Science*, **252**, 1399).

Since the population of short-period comets is roughly an order of magnitude smaller than the family of near-Earth asteroids, the opportunities for cometary radar observations are relatively scarce. Beginning with comet P/Encke in Nov. 1980 (Kamoun *et al.*, *Science*, **216**, 293), radar signals have been successfully returned from the nucleus regions of comets P/Grigg-Skjellerup in May-June 1982 (*BAAS*, **14**, 753), 1983 VII IRAS-Araki-Alcock in May 1983 (*AJ*, **89**, 1745; *ApJ*, **338**, 1071), 1983 V Sugano-Saigusa-Fujikawa in June 1983 (*BAAS*, **15**, 180), and from comet P/Halley in Nov. 1985 (*ApJ*, **338**, 1094). Doppler measurements are available for the first three comets but because of an apparent debris cloud surrounding comet P/Halley, there are no published astrometric radar measurements for this comet's nucleus.

With the relatively recent realization that a large population of near-Earth asteroids are on Earth approaching orbits, there is a critical need to monitor accurate their future motions. For the majority of these objects that lack a long history of optical astrometric data, accurate extrapolations of their motions will require the use of radar data in future orbital solutions.

A complete analysis of the existing asteroid and comet radar astrometric data was presented by Ostro *et al.* (*AJ*, **102**, 1490) for 30 asteroids and 4 comets. Using these radar data and the available optical observations, Yeomans *et al.* (*AJ*, **103**, 303) explained the process by which radar astrometric data are included in orbital solutions and presented orbits for those objects for which radar data existed at that time. Since these publications, Ostro *et al.* (*BAAS*, **23**, 1144) published radar astrometric data for near-Earth asteroids 1990 MF, 1991 AQ, and 1991 JX. In addition, astrometric data have been taken (but not yet published) by S.J. Ostro and colleagues for asteroids 1982 BB (July-Aug. 1991), (7) Iris, (324) Bamberga, and 1991 EE (Sept. 1991), (1981) Midas (Feb.-Mar. 1992), (4) Vesta (Mar.-Apr. 1992), 1990 UQ (May 1992) and (4179) Toutatis (Nov.-Dec. 1992).

Over the period between Nov. 27 and Dec. 18, 1992, the radar observation campaign undertaken by S.J. Ostro and colleagues provided impressive radar "images" of asteroid (4179) Toutatis. In the process, 34 astrometric delay measurements and 21 Doppler measurements were made from JPL's Goldstone radar facility and from the Arecibo radar facility in Puerto Rico. Ranging resolution of 1/8th microsecond (19 m) and Doppler resolution to 0.008 Hz (0.15 mm/s) was achieved, and at least through most of the observation period, the ephemeris prediction errors were smaller than the object itself (less than about 4 km) and primarily limited by the uncertainty in the time-dependent difference between the radar bounce point and the object's center of mass.

Note should also be made of the successful Toutatis radar experiment by Zaitsev *et al.* (ACM'93 abstract, p. 325) whereby the uplink transmitter frequency at the Yevpatoria antenna in the Crimea was modified in accordance with the Toutatis ephemeris so that the downlink signal was received at a constant frequency at the Effelsberg radio antenna in Bonn, Germany. Ten Doppler observations were obtained on Dec. 8–9. The existing optical and radar data, when fully reduced, will make the orbit of this object among the best known in the solar system. Additional radar opportunities will become available for this object during future Earth close approaches on Nov. 29, 1996 (to within 0.035 AU), on Oct. 31, 2000 (0.074 AU) and especially in 2004 when Toutatis will approach the Earth to within 0.010 AU) on Sept. 29.

De Pater *et al.* (in preparation) observed reflected radar transmissions at the VLA from main belt asteroids (7) Iris and (324) Bamberga as well as the near-Earth asteroid 1991 EE in Sept. 1991. On Dec. 17, 1992 a similar observation was made of asteroid (4179) Toutatis using the Goldstone – VLA configuration. Interferometric observations of this type allow two dimensional images to be developed and although the frequency resolution is orders of magnitude coarser than when Goldstone transmits and receives, the Goldstone – VLA configuration has the advantage of creating two dimensional images with 0.25 arcsec resolution at several different frequencies. By comparing the two-dimensional images thus created with the predicted ephemeris positions, interferometric radar observations also allow plane-of-sky angle astrometry to a fraction of an arc second.

In addition to the existing radar astrometric data for several asteroids and comets, Ostro *et al.* (*JGR*, **97**, no. E11, 18 227) presented Goldstone and Arecibo Doppler observations of Europa, Ganymede, and Callisto over the interval from June 1987 through Feb. 1991. Doppler observations were published for Europa (18 observations), Ganymede (23), and Callisto (35). The largest discrepancies between the predicted and observed Doppler observations implied that Callisto may have been lagging its ephemeris by an average of about 200 km.

Arecibo observations from Feb.–March 1992 have yielded the first successful radar ranging measurements to the Galilean satellites of Jupiter. In 1992, Harmon *et al.* (*AJ*, submitted) made range measurements to Ganymede on March 9 and Feb. 20 and to Callisto on 1992 March 3 and March 7. These observations suggest that the required along track position corrections to the ephemeris predictions in that time frame were approximately +122 km for Ganymede, −307 km for Callisto and about +11 km for Jupiter itself. J.H. Lieske is currently making the necessary program modifications to allow the processing of radar data in his Galilean satellite ephemeris development software at JPL.

VI. Occultations (L.H. Wasserman)

VI.I Identification and prediction of upcoming occultations

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Computerized searches for future occultations are being performed independently as before by three investigators. Wasserman, Bowell and Millis published predictions for 1992 and 1993 (55.096.009). Dunham publishes predictions in the *Occultation Newsletter* (*ON*) and an annual summary appears in each January issue of *Sky and Telescope*. Goffin does an independent search. His results appear in *ON* and in the *European Asteroidal Occultation Network* (*EAON*). The chairman of the *EAON* Boninsegna, coordinates European observational activities.

VI.2 Prediction refinement

Astrometric measures for upcoming occultations were provided at various times by Klemola at Lick, by Thirionet at Uccle, by Van Vleck Observatory, and by Lowell Observatory.

VI.3 Observations

There have only been five occultations of minor planets observed during this reporting period which had a sufficient number of chords that a diameter could be determined. Kissling *et al.* observed an occultation by 9 Metis on 1989 Aug. 6 (54.098.088). Buchner reports on an occultation by 521 Brixia on 1989 Oct. 23 (52.098.068). Sato, Soma and Hirose (*AJ*, **105**,1553) report on an occultation by 381 Myrrha on 1991 Jan. 13. This event was especially unusual since the occultation was of the brightest star ever observed in occultation by a minor planet – 1.9 mag γ Geminorum. Observations were also made of an occultation by 4 Vesta on 1991 Jan. 4 and by 216 Kleopatra on 1991 Jan. 19, although the results are still unpublished. In addition, a larger number of other events were observed, but with insufficient chords to determine a diameter. Such events are periodically reported in *ON* and in *EAON*. Oddly, there have been no well-observed occultations in the two and a half years since the three events in January, 1991. A review paper by Millis and Dunham (51.098.149) was published in the book resulting from the Asteroid II conference held in Tucson in 1988.

VII. Asteroid and comet names (A. Carusi)

During the triennium there has been considerable discussion regarding the current procedure of giving names to minor planets and comets. Concerns about the suitability of the procedure were put forward, in view of the already increased number of discoveries and the prospect that even larger numbers of bodies will be automatically detected in the future.

Although the problem is probably not a very urgent one, some of the members of the Commission 20 naming committees feel that a start should be made on revising the naming rules. Other members are uncertain about the necessity of changing a system that apparently works. Nevertheless, the focus should not merely be on its inefficiency, but on its possible complete inadequacy to meet the requirements of reliability and fast response when a hundred thousand objects may be discovered each month.

In particular, it has been proposed that the naming rules for minor planets and comets should be unified, thereby providing a single system for all minor bodies. This unification could solve some of the problems currently presented by objects that are difficult to classify, being observed and classified sometimes as minor planets and sometimes as comets, e.g., the comet P/Wilson-Harrington (1949g = 1949 III), now known as minor planet (4015) Wilson-Harrington.

It is generally agreed that the need for thousands of new names may pose serious problems in the future. A possible solution is the creation of a name bank – including categories proposed by discoverers and scrutinized and accepted by the *MPNC* – from which new names should be extracted.

The name bank could be put on-line, so that discoverers may quickly and efficiently choose names they like. Categorization of special types of names, such as Trojans, AAAs, Centaurs, etc., should be clearly stated and maintained. This method may help resolve the conflicts that take place from time to time: the current naming rules could be applied to entire categories, instead of individual names, alleviating the bi-monthly discussions inside the *MPNC*. On the other hand, discoverers would maintain the privilege of proposing names, possibly assigning to them "tags" for specific objects.

IAU WORKING GROUP ON NEAR-EARTH OBJECTS

REPORT ON ACTIVITY 1991–1994

Convenor: A. Carusi
Members: A. Basilevsky, B. Gustafson, G. Hahn, A. Harris, S. Isobe, G. Lelièvre, A. Levasseur-Regourd, B. Marsden, D. Morrison, A. Milani, K. Seidelmann, E. Shoemaker, A. Sokolsky, D. Steel, Tong Fu, I. Williams.

I. Introduction

The Working Group on Near-Earth Objects (*WGNEO*) was created by the IAU at its XXIst General Assembly in Buenos Aires, Argentina, August 1991, to allow the interaction of astronomers working in a variety of fields. Members of the *WGNEO*, from Commissions 4, 7, 9, 15, 16, 20, 21, and 22, were convened by Andrea Carusi, President of Commission 20.

The main scope of the *WGNEO*, as outlined by the Resolution adopted at the XXIst General Assembly, was to "assess and quantify" the potential threat posed to our planet by impacts of asteroids and comets, to "pool resources" for their discovery and follow-up, and to "act as an international focal point", seeking cooperation with scientists in different disciplines.

The *WGNEO* has worked for three years, with active participation of its members. This Report contains an outline of its scientific evaluation of the problem, together with some suggestions for future activities.

The *WGNEO* concurs with the judgement that cosmic impacts represent a significant natural phenomenon that has played an important (perhaps critical) role in the past evolution of life on Earth, and that such impacts represent a continuing threat that should be considered and dealt with on an international basis. Both the accelerating rate of discovery of near-Earth asteroids (and comets) and studies of the potential environmental consequences of large impacts have enhanced scientific and public interest in cosmic impacts since the 1991 General Assembly. We anticipate that this interest and concern will continue as we learn more about NEOs.

II. Scientific overview (D. MORRISON)

During the past three years the known number of near-Earth asteroids (NEA) has nearly doubled, and one was discovered passing less than 150,000 km from Earth. The break-up of Comet P/Shoemaker-Levy 9 (1993e) and the anticipated collision of several of its fragments with Jupiter in July 1994 provide a visible example of planetary impacts by NEOs. Radar investigations of Toutatis during its close flyby of Earth in 1992 led to the first detailed images of a NEA, and the first spacecraft mission (Clementine, a US Navy spacecraft to fly past 1620 Geographos in 1994) is nearing readiness for launch. In addition, major international scientific meetings dealing with the NEOs and their impact threat have been held in Flagstaff (USA), San Juan Capistrano (USA), St. Petersburg (Russia), Liège (Belgium), Tucson (USA), Erice (Italy), Belgirate (Italy) and Sagamihara (Japan). Several more are planned for 1994. Detailed studies of the impact problem and possible ways of dealing with it have been completed by two working groups of NASA (USA) and presented to the U.S. Congress, and a comprehensive multi-author book on the subject is being published by the University of Arizona Press. All of these efforts have focused attention on the impact hazard and led to an improved understanding of the phenomena involved.

In any given year the probability of an impact large enough to do significant harm is small, but not negligible. In the long term, such impacts can be expected to result in catastrophes of a magnitude that equals or exceeds that of any other natural phenomenon, such as severe storms, volcanic eruptions, or earthquakes.

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The collision of small asteroids or comets with the Earth (diameters less than a few tens of meters, impact energies less than about 10 megatons) can result in spectacular fireballs or bolides but generally do comparatively little damage on the ground. However, the atmospheric disintegration of such a body has the potential of being mistaken for a nuclear explosion at a time of international tension. Education concerning the nature of these events and their frequency is important if we are to avoid their misinterpretation as nuclear attacks.

Surface impacts or lower-atmosphere explosions of objects with energy greater than about 10 megatons (and perhaps 50 m in diameter) are capable of inflicting severe local or regional damage; such events are expected to take place approximately once in a few centuries. Ocean impacts of objetcs having energies greater than 1000 megatons and diameters of a few hundred meters have an especially large potential for damage to coastal regions resulting from tsunamis. Larger impacts, corresponding roughly to impacting objects having diameters greater than 1-2 km, generate global consequences, especially through injection of dust into the stratosphere. Such impacts, which are believed to occur on time-scales of hundreds of millennia, could produce short-term climate fluctuations, lead to widespread loss of crops and mass starvation, and destabilize modern civilization. Still larger impacts, occurring on time-scales of millions of years, could lead to mass extictions of species and alter the course of biological evolution.

Both the probabilities of impacts of various sizes and energies and their anticipated consequences have large uncertainties. It is estimated that fewer than 10% of NEAs with diameters greater than 1 km have been discovered, and our knowledge of the cometary population at these sizes is even more uncertain. Evaluation of the threat of cosmic impacts requires a better understanding of the population of comets and asteroids and also of their physical and chemical nature. Such information can be obtained from a combination of astronomical searches for NEOs, follow-up studies of their physical properties using optical and radar astronomy, and visits to a few representative objects by spacecraft. Such studies are of great scientific importance for understanding NEOs and their role in solar system history as well as for evaluating the impact threat. They are also a prerequisite for any efforts to develop strategies for deflecting an incoming object or mitigating the consequences of its impact.

III. Present and future search programs (E.L.G. Bowell, G. Hahn, A.W. Harris, D.I. Steel)

III.1 Present search programs

There are currently four dedicated near-Earth object search programs in operation (three in the U.S.A., one in Australia). From time to time, NEOs are discovered by other researchers, especially those using Schmidt telescopes. Indeed, wherever wide-field plates are taken, observers are encouraged to search them for tell-tale trails, since these represent a data source which is largely unexploited; the extensive plate libraries that exist also contain some thousands of unrecognized trails from NEOs yet to be discovered.

The longest-operating program is the *Planet-Crossing Asteroid Survey (PCAS)*, at Palomar, which was begun in 1972 under E.F. Helin (JPL) and E.M. Shoemaker (USGS). Ten years later, Shoemaker initiated the *Palomar Asteroid and Comet Survey (PACS)*, which has similar but distinct aims. The two programs use the same instrument for their data collection (the 0.46 m Schmidt at Palomar Mountain Observatory in California) and similar analytical techniques. Pairs of short-exposure photographs are inspected using stereomicroscopes to search for moving objects down to $V = 17.5$. Both teams cover about 40 000-50 000 square degrees of sky a year, and each discovers about a dozen near-Earth asteroids and several comets per annum as a result.

The third U.S. program is undoubtedly the most sophisticated world-wide. The *Spacewatch Telescope* (University of Arizona), with a long focus and a 0.91-m aperture, began operations in the late 1980s. This instrument is used in scan mode, with the RA drive switched off, so the sky is swept at sidereal rate. A large-format CCD is read out at the same rate to produce a scan about 40 arcmin wide and as long as the observation is produced (about 30 minutes of time). The target region is then twice re-scanned. A comparison in real time of the three scans then allows moving objects to be identified. Since the *Spacewatch* instrument is able to detect not only large NEOs at substantial geocentric distances but also nearby (cis-lunar) objects as small as 5-10 meters in diameter, it has been possible to fill the gap in the size-frequency plot between bright meteors and small asteroids. With good conditions the *Spacewatch* team may discover several NEOs in a month.

The only program located in the southern hemisphere is the *Anglo-Australian Near-Earth Asteroid Survey (AANEAS)*, begun in 1990. All plates and films taken with the 1.2-m U.K. Schmidt Telescope are searched for asteroid trails, those of unusual length or orientation being followed up. About 40 000 square degrees per year are covered to a limiting asteroidal magnitude of about V = 19. The discovery rate of NEOs is currently about 10 a year.

III.2 Future projects

For the future, there is a widespread belief among NEO researchers that an observational system like the proposed Spaceguard Survey is necessary. As described in *The Report of the Near-Earth-Object Detection Workshop* (NASA, 1992), an NEO survey lasting at least two decades would be carried out using a worldwide network of perhaps six 3-m-class telescopes. By scanning several thousand square degrees of sky up to ten times per month, and to a limiting magnitude V = 22, it should be possible to discover about 90% of NEAs larger than 1 km in diameter. Earth-crossing comets are harder to discover because many of them have long orbital periods. Overall, it is estimated that about three quarters of all NEOs larger than 1 km diameter could be discovered during the course of a 25-year Spaceguard Survey, though it is anticipated that improvements in technology will lead to even greater NEO discovery rates.

Meanwhile, a number of groups are undertaking the precursor research for a major effort like Spaceguard. In the U.S., the *Spacewatch* team is concentrating on installing a 1.8-m telescope; a group at JPL is investigating the use in NEO searches of one or more of the 1-m wide-field telescopes currently used by the U.S. Air Force for tracking Earth satellites; and at Lowell Observatory, a 0.41-m Schmidt telescope is being refurbished with a mosaic-CCD camera. In Europe, the *EUNEASO* initiative (*EUropean Near-Earth Asteroids Search Observatories*), consisting of groups at the OCA (France), DLR (Germany), Uppsala Observatory (Sweden), and Helsinki Observatory (Finland), is working to equip the 90-cm Schmidt telescope at Caussols (OCA) with a CCD-array camera, and run it as a search station. The possibility of a second search station at ESO (1-m Schmidt), La Silla, Chile, is currently being investigated. Several other stations are planning to participate as follow-up and/or physical observation sites; e.g., Ondřejov (Czech Republic). In addition, national efforts are being planned in Italy and Russia, as precursor projects. In Australia, the *AANEAS* program is being expanded to make use of the UKST during bright-of-Moon time when that instrument is normally unused, employing the stereo pair technique pioneered by the *PCAS* and *PACS* teams. There is broad recognition that ramping up toward a Spaceguard-like survey entails research in a number of areas, including the development of more sophisticated image-detection software than currently exists, the processing of large numbers of asteroid and comet detections, the efficient design of follow-up strategies, and the planning of physical observations. Consequently, healthy collaborations are developing among researchers to share their expertise and workload.

It should be noted that such programs, while aimed principally at the detection and follow-up of NEOs, will yield as a spinoff a huge increase in the inventory of solar system objects (main belt asteroids, Trojans, Centaurs, distant bodies). Thus, there are benefits to scientists other than planetary astronomers in designing and conducting extended NEO surveys.

III.3 Radar observations

Radar astrometry represents a very powerful mean for NEO studies. As a matter of fact, radar observations are capable not only to provide information on the physical characteristics of the bodies under study, but also to help in the refinement of their ephemerides.

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A comprehensive review, by D.K.Yeomans, of the researches done in this field in recent years may be found in the report of IAU Commission 20 (this volume). Here we want only to stress the usefulness of this technique in NEO searches. The results obtained in 1992 with the radar observations of (4179) Toutatis, at its passage close to the Earth, have clearly shown that these studies may become of primary importance in the future.

IV. Follow-up programs (B.G. MARSDEN)

If and when a full-fledged NEO detection program like Spaceguard is undertaken, most of the necessary astrometric follow-up will occur automatically, as part of the scheduling of the observations. It is to be expected that the field in which a discovery is made will be reobserved a night or two later. Furthermore, there is merit to arranging for the field to be scanned on one of these nights both well east and well west of the meridian; not only will the shorter time difference simplify the linkage, but the resulting diurnal parallax will help the initial orbit determination. The same could be accomplished with observations from a different site, although unless there is a considerable difference in latitude the observations should be made at substantially different local times.

Two-night detections can automatically be inspected for identifications with earlier objects for which there are orbits in the database, even if these are of quite poor quality. New discoveries of particular interest can be flagged anyway. In automatic mode, the same general fields should also then be covered in the same way on two more nights later in the dark run. The database will at that point include some kind of orbital representations for the objects detected earlier in the month, so any rediscovery of the same object will immediately become apparent, after which a better orbit, compromising a 10-15-day arc, can obviously go into the database.

As noted in Sec. II.2 of the report of Commission 20, the current international effort on minor planets involves well over 100 observatories (15 or more very actively), the discovery of more than 4 000 unidentified objects each year, and an annual total that is well in excess of 40 000 published astrometric observations. Estimates made in connection with the discussion of Spaceguard suggest that this could became the rate of detection of actual or suspected NEOs alone, while the total activity might be two orders of magnitude higher.

If this should come to pass, there should be no real difficulty handling the data, even if the available computers were only one order of magnitude faster than those used in work on minor planets at present. Most of the time spent at present is caused by poor or unbusinesslike communications and the slowness of reducing photographic data and their frequent unreliability – notably the errors that often arise in the quoted times of observation. When CCD astrometry is carried out by an organized team – even a team of amateur astronomers – and the observations are reported in an efficient manner that minimizes any necessary reworking of the data, identifications can be made and orbits can be computed very rapidly. Another source of wasted time at the present is the manner in which the astrometric and orbital data are collected together specifically for publication in printed material according to a fixed schedule – like the monthly *Minor Planet Circulars*. Although this material is currently also available electronically, the orientation toward the printing schedule and the need to publish material that is internally consistent makes it more difficult to ensure that the very latest orbital elements and ephemerides are always available to those making further observations, particularly physical observations using telescopes that may have fields of view on the order of only 1 arcmin.

The reality of the moment is that much of the astrometric follow-up of NEOs is currently being done by the four principal discovery programs. Specific follow-up astrometry is carried out at the Oak Ridge Observatory in Massachusetts, at the University of Victoria and Dominion Astrophysical Observatory, at Mt. John University Observatory on New Zealand's south island, as well as by several amateur astronomers, notably in Japan and Italy. The growing amount of amateur involvement is an encouraging sign, but almost without exception, these are small-field instruments. Although extensive follow-up clearly detracts from the search activities themselves, it is therefore essential that accurate positions be quickly and reliably made available from the discovery data and that the wide-field instruments of the discoverers themselves be used for the second-night confimation – and further observations too if the initial recognition of a NEO is significantly delayed.

In the absence of other identifications, astrometric follow-up should be continued (on two nights each dark run) for as long as possible at the initial apparition. This minimizes the search area that will need to be covered to find the object in later years. Many NEOs are discovered on particularly favorable passages, and it is therefore these same apparitions that should be utilized for obtaining physical follow-up, notably three-colour (or more) photometry in order to establish quantities such as radius, albedo and rotation period. If an object comes close enough to the Earth, radar observations should also be made for both astrometric and physical purposes.

V. International context (A. Carusi, B.G. Marsden, P.K. Seidelmann)

V.1 General considerations

The threat posed by NEOs makes no distinction by political boundaries: the entire planet is at risk. This international character of the hazard requires an equally international response.

There are at least three reasons why searches for NEOs should be overseen, in the long run, by an international agency:

- Scientific investigations devoted to the discovery and follow-up of NEOs, to the understanding of their physical nature and of the dynamical mechanisms that deliver them in the inner regions of the solar system, as well as to the possible phenomena associated with an impact, are best conducted in an international context, where a free exchange of knowledge and skills may allow a synergistic effort and therefore an optimal result. A close connection with international bodies other than the IAU should be established to broaden the interest in NEO searches. As an intermediate step, we recommend that an inter-union working group be formed as soon as possible.

- Research and experiments on defense systems are a very delicate issue, which involves people and assets formerly involved with the Cold War. It would be at least prudent that any decision and directive on these matters be discussed and agreed upon in an international forum.

- Political and social initiatives regarding NEO searches have a higher probability of success if the enterprise is international in nature. In particular, sharing resources and costs is especially applicable to efforts such as the proposed Spaceguard Survey, which require the establishment of observational and communication networks.

Since NEOs discovered in the northern hemisphere can quickly move to the southern (and vice versa), follow-up of NEOs is necessarily an international activity. The number of professional astronomers involved in NEO follow-up at present is extremely small. Further participation is actively encouraged, particularly by those with access to moderate-to-large-aperture telescopes that can follow discoveries to magnitude 20 and fainter. It is perhaps unfortunate that the principal discovery programmes also have to conduct a large part of the follow-up, but unnecessary duplication could even now be eliminated if there were greater cooperation among these programs.

A few words should be devoted to the prospects for radar observations. The Toutatis radar experiment by Zaitsev *et al.* (ACM'93 abstract), using the Yevpatoria antenna (Crimea) as the uplink transmitter and the Effelsberg radio antenna (Germany) as the downlink receiver, has opened a new field for international cooperation. No plans have yet been made, however, for coordinated efforts using radars.

Apart from the *WGNEO*, there are already other organizations at work which are international in character. This is the case, for example, of the scientific network *Role of Impact Processes in the Geological and Biological Evolution of Planet Earth*, of the European Science Foundation,

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chaired by Dr. D. Stöffler (Germany). It should also be stressed that the *Minor Planet Center* and the *Central Bureau of Astronomical Telegrams*, operated by the Smithsonian Astrophysical Observatory in Cambridge (USA), are in a way an international agency, operating under the auspices of the IAU.

V.2 WGNEO Recommendations

The IAU *Joint Working Group on Near Earth Objects* recognizes that:

1. our current knowledge of the quantity, distribution, and actual orbits of Near Earth Objects is very limited,

2. an inventory of NEOs as complete as possible with present techniques, is only possible through a cooperative, coordinated program of observation and data collection,

3. cosmic impact is an environmentally significant phenomenon which has played a major role in the evolution of life on Earth,

4. in any given year there is a very low probability that a large cosmic impact may occur which would destroy human civilization or even a significant fraction of life on Earth. However, the threat is real and requires further internationally coordinated, public educational efforts,

5. a significant near term cosmic impact threat is a naturally produced, atmospheric explosion of a small Near-Earth Object being mistaken for a nuclear explosion, at a time and place of international tension. These events have been observed. Such an event could be misinterpreted as a nuclear attack and trigger an unfortunate reaction,

6. the gathering of additional physical knowledge on Near Earth Objects and their effect on Earth is a scientifically and socially important endeavor. These multi-disciplinary efforts should be conducted in an open, coordinated, international manner. Dedicated international astronomical facilities similar to the proposed *Spaceguard System* should be developed. The assets and technologies of many countries can contribute to the gathering of these data, through ground and robotic space observations. The skills and technologies, necessary for any large, complex investigation, should be utilized,

7. unless a specific and imminent threat becomes obvious, actual construction and testing of systems that may have the potential to deflect or mitigate a threat may be deferred because technology and systems will improve,

and, therefore, recommends that:

1. a coordinated, international search program be initiated to detect all Near-Earth Objects, brighter than 20th magnitude,

2. the *Minor Planet Center* perform the functions of the collection of observational data and the determination of accurate ephemerides,

3. capabilities for obtaining accurate astrometric observations, as necessary to determine accurate ephemerides be established,

4. coordination between scientific and humanitarian organizations and governments be encouraged concerning NEOs,

5. an international source for accurate and responsible scientific information on NEOs be established and available to the media,

6. the *Working Group on NEOs* be continued to fulfill the above recommendations.

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