2. X-RAY ASTRONOMY

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1. Introduction

X-ray astronomy has continued to flourish in the three years covered by the present report (to June 1987) despite the continuing scarcity of new missions. The European EXOSAT has probably made the greatest impact during this period, carrying out over 2000 separate observations up to it's loss of attitude control in April 1986. A major reason for the success of EXOSAT was the unusual spacecraft orbit which provided uniquely long source exposures, uninterrupted by Earth occultation, of up to 70 hours duration. The continuous light curves of many galactic and extragalactic sources have proved particularly valuable in studying details of time variability over a broad frequency range and in this respect the EXOSAT data archive is unlikely to be superceded in this century. For several months after the demise of EXOSAT, astronomers had no operational X-ray satellite for the first time since the launch of Uhuru in 1970. This unfortunate state of affairs ended in February 1987 with the successful launch of the Japanese ASTRO-C satellite. Three months later, observations began with several X-ray instruments on board the Soviet MIR space station and at the time of writing both GINGA (the post-launch name of ASTRO-C) and the MIR instruments are working well.

Looking ahead, future X-ray missions are generally no closer to realisation than they were 3 years ago, a gloomy situation which, in major part, is a consequence of the Shuttle Challenger accident in January 1986. The German ROSAT X-ray telescope now appears likely to be the next major launch, probably early in 1990 on a Delta 2 vehicle. Present plans indicate a probable launch of the US Extreme Ultraviolet Explorer mission, also on a Delta 2 rocket, in $\sim$ 1990. The two 'world class' X-ray projects, NASA's AXAF and ESA's XMM 'cornerstone' mission, are now unlikely to fly before the latter half of the 1990's. A major new Soviet initiative, Spectrum-X, involving substantial participation by W. European groups, may now precede both.

In overview, although launch delays have inevitably slowed the pace of X-ray Astronomy, remarkable and important discoveries continue to be made (examples in the present report include, QPO's, rapid variability in Seyfert nuclei, and red-shifted X-ray line emission from SS 433) and a healthy development is the much broader international community now active in X-ray astronomy than was the case in earlier years. The following sections provide a brief progress report of X-ray astronomy for the period since the Commission's 1982 report.

2. The X-ray Background and Cosmology

The nature of the intense and near-isotropic sky background X-ray flux discovered in the first rocket exposures of the early 1960's has remained an intriguing puzzle to the present day (see Boldt, 1987, for a recent review). Although it is widely believed that the X-ray background (XRB) is primarily due to the integrated emission of many unresolved sources at high redshift, present data require a substantial extrapolation in the observed source counts of different classes of active galaxies (AGN), the favoured candidates. In addition, the present spectral data of AGN and the XRB appear incompatible. A re-analysis of fluctuations in the XRB based on Einstein Observatory IPC data by Hamilton and Helfand (1987) has recently supported an earlier suggestion that the luminosity function of the constituent sources flattens just beyond the Einstein Deep Survey limit (at present the faintest sources directly resolvable), implying that a major fraction of the XRB must arise from a strongly evolving population of very faint (and presently unknown) sources, or be of truly diffuse nature (which requires an uncomfortably large total energy density of the baryonic component of the Universe). It seems unlikely that this fundamental question will be clearly answered until future, large and high resolution, X-ray telescopes are available to directly resolve the XRB. In the meantime, useful progress may be expected from smaller missions, such as GINGA, which may be capable of checking whether the X-ray spectra of distant quasars are more like that of the XRB than the nearer AGN and the deep exposures of ROSAT which will extend the direct limits of the Einstein Observatory by almost an order of magnitude (Trumper, 1984).

3. Active Galactic Nuclei (AGN) and clusters of galaxies

Continued study of the Einstein Medium and Deep Survey data has yielded X-ray fluxes of many quasar-like objects and allowed quantitative assessment of the X-ray emission of different sub-classes of AGN, such as radio-loud and radio-quiet QSO's (Tananbaum et al, 1986; Worrall, 1987).

Perhaps the most significant recent progress in the AGN area has resulted from EXOSAT observations. First, a number of Seyfert 1 galaxies have been found to have a complex X-ray spectrum, with an up-turn to low energies near 1 keV (Arnaud et al, 1985; Pounds et al, 1986a). The discovery that the 'soft excess' varies on timescale as short as a few hours in some cases supports the view suggested in both the above references that the low energy X-ray component arises as thermal emission from the innermost regions ($T \sim 10^5$ K) of a accretion disc. The second EXOSAT discovery, that rapid variability (down to the typical detection limit $\sim 10^3$ s for faint AGN) is common in Seyfert 1 galaxies, has lent further support to the view that these objects are indeed powered by accretion onto a massive black hole. Light travel time arguments have been used to suggest masses of the central hole in the range $10^6 - 10^7$ $M_\odot$ (Pounds et al, 1986a,b).

Improved X-ray spectra of many bright clusters of galaxies, obtained with EXOSAT, have shown strong correlations between the intercluster gas temperature, the X-ray luminosity and the velocity dispersion of the constituent galaxies (Edge et al, 1988) Such data are important to obtaining an understanding of the evolution of the cluster gas and spectral data on more distant clusters (perhaps with GINGA) are eagerly awaited.

Further studies of the cooling flow phenomenon in clusters have revealed one remarkable example, PKS 0745791, where the mass flow rate is of the order of 1000 $M_\odot$ per year (Fabian et al, 1985) and a second with a cooling flow of red shift 0.39 (Fabian et al, 1987).

4. Normal galaxies

Analysis of Einstein data for complete samples of spiral and elliptical galaxies have shown (Fabbiano and Trinchieri, 1985; Trinchieri and Fabbiano, 1985) that strong correlations exist in both types, for example, between the X-ray and blue-band luminosities. The major component of the X-ray emission in the spirals is thought to arise in X-ray binary systems (as in our Galaxy), whilst in ellipticals the emission is mainly from hot gas at $kT \sim 1$ keV. In the latter case the amount of hot gas (typically $\sim 10^9$ $M_\odot$) is too large to associate with a galactic wind and probably must be gravitationally bound. This leads, in turn, to the implication of massive haloes of dark matter in elliptical galaxies (Forman et al, 1985; Nulsen et al, 1984).

The typical densities of X-ray-emitting gas in the elliptical galaxies are such that cooling flows are likey to be important here too, with the intriguing consequence that star formation is probably still occurring in elliptical galaxies, contrary to the conventional view. The EXOSAT observations of M87 provide a particularly clear case of a large 'dark halo', an extended spectral map of the galaxy showing a constant gas temperature (kT ~ 2 keV) out to ~ 500 kpc (Edge, Smith and Stewart, 1987), requiring a mass-to-light ratio ~ 500.

5. Supernova remnants and the ISM

The wealth of X-ray images and spectral data from many galactic and Local Group supernova remnants provided by the Einstein Observatory has now been extended with resolved spectra out to ~ 10 keV. The GSPC instruments on EXOSAT and TENMA have yielded the best recent data in this band, showing the expected strong line emission of helium-like Fe, Ca, Ar and S from young remnants such as Tycho, Kepler, Cas A, RCW 103 and W49 B (Smith, 1987; Tsunemi et al, 1986). Analysis of all available X-ray data has shown simple models of the X-ray emission to be invalid, with clear evidence for non-equilibrium ionisation (NEI) in remnants even as old as Puppis (Winkler et al, 1983). The general trend is that fitting with NEI models considerably reduces the large mass estimates of the heated gas (to ~ 1 - 3 solar masses in most cases), while still leaving a significant over-abundance of metals. Undoubtedly, much remains to be learned about the nature and evolution of SNR from spatialy resolved X-ray spectroscopy offered by future missions such as AXAF and XMM.

6. Low mass X-ray binaries

X-ray binary systems containing a neutron star component, which include most of the brightest X-ray sources in the night sky, conventionally are sub-divided by mass of the optical counterpart. Progress over the past 3 years has been most rapid in the study of the low mass systems (LMXRB's), mainly due to the broad band spectroscopic data from TENMA and EXOSAT and the long, continuous observations and high time resolution data from EXOSAT. The detection of periodic 'dips' in the X-ray light curves of several LMXRB's has yielded the first orbital periods (as expected, typically of the order of a few hours), in addition to offering an important probe of the accretion disc structure in such systems. For example, in the 'dip' source 4U1755-33, White et al (1984) have used X-ray spectral data from EXOSAT to show the accreting material to be under-abundant in heavy elements by a factor > 100. Recent broad band X-ray spectra of several LMXRB's have been shown to contain two separate components, a black body component (arising from the heated neutron star surface?) and a softer component, which probably originates in the inner accretion disc (see review by White, 1986).

Probably the most intriguing new result in the study of the LMXRB's has been the discovery of quasi-periodic-oscillations (QPO's), with frequencies in the range ~ 1 - 30 Hz. GX5-1 was the first source found to exhibit QPO's (van der Klis et al, 1985) and the correlation of the frequency and width of the QPO peak with source intensity led to an initial explanation in which the QPO was related to 'beating' between the rotation of material at the inner edge of the accretion disc and the neutron star surface. More recent observations have shown a much more complex picture and it now seems unlikely that one description applies to all cases (see Lewin, 1986, for a review).

Further details on the properties of X-ray bursts, generally associated with LMXRB's having neutron stars of low magnetic field, have come from both EXOSAT and TENMA. The simple thermonuclear flash model has been shown to be inadequate, with the discovery of multiple peaks in several bursts (e.g. van Paradijs et al, 1986) and also series of bursts too closely spaced to allow complete fuel replenishment by accretion (Lewin et al, 1987). Fujimoto et al (1987) have proposed that hydromagnetic instabilities in the accreting matter cause pockets of unburnt material to spiral deep into the neutron star's atmosphere, producing partial ignition. Other bursts have shown evidence of radial expansion of the entire X-ray photosphere, with a tendency for luminosity saturation. Separate saturation levels have been associated with Eddington-limited accretion in helium-and hydrogen-dominated atmospheres. The X-ray absorption feature identified in several burst spectra by TENMA (Waki et al, 1984) and EXOSAT (Turner and Breedon, 1984) has continued to inspire theoretical study, mostly based on an interpretation as a gravitationally red-shifted Fe-K feature. The existence of this spectral feature has recently been confirmed by GINGA observations, but the red-shift is apparently too large for standard neutron star models (Lewin, 1984) and the feature too strong for production in a conventional atmosphere (Foster et al, 1987).

7. High mass X-ray binaries/black hole candidates

For over a decade Cygnus X-1 had the unique status of being the only X-ray binary for which there is compelling evidence for the compact object having a mass > 3 $M_{\odot}$ - thus probably being a black hole. New optical data of the remarkable Ariel-5 X-ray transient A0620-00 now strongly suggest that this system too contains a black hole (McClintock et Remillard, 1986). Interestingly, one of the previously favoured black hole candidates, Circinus X-1, has now been shown almost certainly to be a neutron star source, following the discovery of X-ray bursts in a long EXOSAT observation (Tennant et al, 1986).

Although SS 433 is almost certainly a high mass XRB, it is well known primarily for its relativistic jets. New insight on the jets has been provided by EXOSAT and TENMA observations which show that the Fe-K line moves in energy in a manner consistent with Doppler shifts from material in the inner jet regions (Watson et al, 1986). Analysis of these data has provided constraints on the dimensions of the emission region and on the energetics and acceleration mechanisms in the jets.

8. Globular cluster sources

The first optical identification of an X-ray source in a globular cluster was made in the case of M15 (NGC 7078) by Charles et al (1986). This identification was based on coordinated EXOSAT observations and optical photometry and spectroscopic studies of the star AC 211. The remarkable discovery of an 11 minute (!) modulation in the X-ray flux of a second globular cluster source, 4U 1820-30 (by Stella et al, 1987) and a lack of period variations has yielded the shortest known orbital period of any stellar system. The difficulty of such a system evolving from a longer period binary suggests it must have been formed by neutron star capture - a possibility presumably most likely to occur in the dense core of a globular cluster.

9. White dwarf binaries /Cataclysmic variables (CV's).

A considerable amount of EXOSAT observing time was devoted to the study of cataclysmic variables, both in outburst and in quiescence. As a result, it is now clearly established that CV's containing a magnetised white dwarf star typically have substantially higher X-ray luminosities than non-magnetic systems. Also, the strongly magnetised systems, or polars, have a strong soft X-ray flux which - in some cases at least - is much greater than the hard X-ray emission. X-ray light curves of intermediate polars (magnetic systems with a lower field) show the X-rays to arise from large polar caps (e.g. Watson and King, 1985).

Important new results for non-magnetic CV's include evidence for coronal emission in SS Cygni (King et al, 1985) and the detection of 14 sec. pulsations in the superoutburst of the SU UMa system VW Hyi (van der Woerd et al, 1987).

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10. Stellar X-rays

The most active, and X-ray brightest, cool stars are the RS CVn binaries. Several of these have been well studied for one or more orbital periods. A lack of evidence for X-ray eclipses in Algol (White et al, 1986) and ER Vul (White et al, 1987b) indicate that the coronal scale heights are > 1 $R_\odot$. By contrast the existence of a deep minimum in the flux observed by the EXOSAT LE telescope, centred on the primary eclipse of AR Lac (White et al, 1987a), has allowed a detailed model of the system to be developed, where a plasma of 5 - 7 x 10^6 K is closely confined to the two small regions of the G star and a higher temperature component (15 - 30 x 10^6 K), associated with the K star extends to ~1 $R_\odot$.

Broad band EXOSAT observations of RS Cvn's suggest that coronal X-ray emission typically arises from components at two different temperatures (~ a few x 10^6 K and ~ a few x 10^7 K). While this simple model is very useful, EXOSAT transmission grating observations (Mewe et al, 1986; Schrijver and Mewe, 1985) show a more complex picture of plasma having a continuous temperature distribution, but with the differential emission measure distribution peaking at the above temperatures. This is incompatible with simple static loop coronal models and other models (e.g. quasi-static loops of varying cross-sectional area or dynamic loops with strong downward flow) must be considered.

A number of high resolution spectra of hot DA white dwarfs were also obtained by EXOSAT (e.g. Paerels et al, 1986), allowing improved temperature measurements of their objects and a detailed study of their atmospheres, in particular placing tight constraints on the abundances. The photosphere of HZ43 is found to consist solely of H, presumably the result of uninterrupted downward diffusion of heavy elements in the strong gravitational field. A photometric survey of 21 DA white dwarfs (Heise, 1987) has revealed that many of these objects have traces of He in their atmospheres. Further analysis of this sample should allow determination of the relative importance of radiative support, convective mixing and accretion from the interstellar medium on white dwarf evolution.

Finally, EXOSAT observations have enabled the first soft X-ray detections of the hottest, He-rich DO white dwarfs (Barstow, 1987), at temperatures exceeding 10^5 K. Some of these objects are optical pulsators and one, PG1159-035, was also found to be an X-ray pulsator (Barstow et al, 1986). This is the first observation of photospheric X-ray pulsations. The relative phases and amplitudes of the various X-ray and optical modes are a sensitive probe of the atmospheric structure of white dwarfs.

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