SOME CONSIDERATIONS RELATING TO AN INTERSTELLAR ORIGIN FOR COMETS

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INTRODUCTION

The idea that the Solar System possesses a primordial isotropic cloud of comets has been with us in quantitative form for about thirty years (Oort 1950). A considerable edifice has been built on this proposition (e.g. Weissmann 1982), which has proved durable despite indications that the cloud may in fact be significantly non-thermal and display Galactic alignments (Tyror 1957, Richter 1963, Oja 1975, Yabushita et al. 1979, Radzievsky 1981). However with the discovery in recent years of a system of massive molecular clouds in the Galactic disc, it has become apparent that the environment in which the Oort cloud has to survive is very different from that envisaged in 1950; a re-appraisal of the standard picture is therefore called for.

One corollary of the discovery of the molecular clouds is that the traditional objections to an interstellar comet cosmogony, such as the lack of observed hyperbolic comets and the difficulty of growing and capturing them, may no longer apply (see for example the recent review by Clube & Napier 1982a, hereinafter CN). Another consequence, reviewed here, is that tidal effects due to molecular clouds may be so large that the Oort cloud is frequently disrupted (CN; Napier & Staniucha 1982). In this situation frequent replenishment is implied and it is therefore necessary to discriminate between the primordial and the observed Oort cloud and to consider possible alternative sources for the latter. Such an enquiry would provide constraints on the as yet unsolved problem of comet formation.

In the Table is summarised the classes of theory that might explain the Oort cloud. Oort himself for example has seen the comets as basically fragments of a proto-planet; but the subsequent trend (e.g. Cameron 1973) has been towards manufacturing comets further out. If the Oort cloud is indeed continuously depleted as a result of tidal forces, the idea that it is fed from a massive invisible inner cloud (e.g. Hills 1981, van den Bergh 1982, Bailey 1982) or planetary source (e.g. Vsekhsvyatsky 1967, van Flandern 1978) becomes attractive. On the other hand, if there is no such inner source, the possibility of capture

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from outside the Solar System has to be considered. In this connection the realisation that efficient 3-body capture mechanisms exist is relevant (CN, Valtonen 1982). Thus it has been shown that, for reasonable assumptions about comet densities in the star-forming regions of molecular clouds (e.g. Trapezium systems), the Sun might easily capture an entire Oort cloud during transit. Omitted from the Table are theories which dispense with an Oort cloud altogether; the hypothesis of Lyttleton (1953) is a conspicuous example in this category. To its credit Lyttleton's work faces up to the difficulty of actually making comets; however it has not so far met other difficulties (e.g. Öpik 1966) and has not accounted for the dirty snowball model (Whipple 1950) which has had some success in explaining the observations.

TABLE

Hypotheses regarding origin of Oort Cloud

Hypothesis	Implied Origin	Chemical Age	Proposed by
Protoplanetary ejecta	Primordial	4.5×10^9y	Oort/Öpik
In situ condensation	Primordial	4.5×10^9y	Cameron
Perturbation of inner cloud	Replenished	4.5×10^9y	van den Bergh Hills Bailey
Planetary satellite ejecta	Replenished	4.5×10^9y	Vsekhsvyatsky van Flandern
Capture from GMCs	Replenished	$10^7 - 10^8$y	Clube & Napier Valtonen

It should be noted that, save for the capture one, all the hypotheses of the Table would have comets made of primordial Solar System material. The development of techniques for measuring the ages of cometary particles gathered from the terrestrial environment (e.g. Papanastassiou et al. 1982) is thus of critical importance to the capture hypothesis; but with such results not yet forthcoming, we consider here some other evidence that can be adduced in favour of episodic disturbance and frequent replenishment of the comet cloud.

Evidence for episodic disturbance

It has been suggested in a series of papers (Clube 1978; Napier & Clube 1979; CN; Clube & Napier 1982b) that an episodic and calculable history of terrestrial catastrophism is in principle derivable from the assumption that the Solar System periodically encounters molecular clouds during passages through the spiral arms of the Galaxy. These encounters overturn the Oort cloud, flood the loss cone of the planetary system and so lead to episodes of bombardment with Galactic periodicity (50-200 Myr). Specific geophysical predictions follow from the theory; *inter alia*, major extinction boundaries due to the impact of 10^{18}-10^{19} g bodies should occur and correlate with violent plate tectonic phenomena and with episodes of magnetic polarity reversal. The latter, caused by impacts of the more common 10^{16}-10^{17} g bodies, should be sudden in onset and decline in 20-30 Myr. Such correlations, with a Galactic periodicity, do indeed occur and are seen here as fundamental and hitherto unexplained aspects of the terrestrial record (McCrea 1981). The effects are illustrated in Figure 1 for the recent Phanerozoic; it should be noted in particular that the famous dinosaur extinction of 65 Myr ago was proposed to be due to 10^{18}-10^{19} g impact, on the basis of this hypothesis, well *before* the geochemical discoveries at the boundary apparently confirmed the fact (cf Napier & Clube 1979 with Smit & Hertogen 1980 and Alvarez el al. 1980).

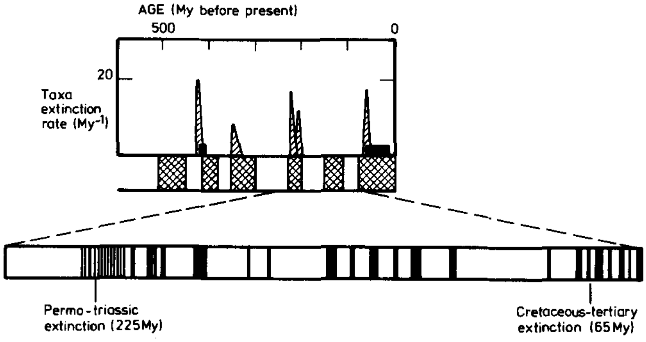

Figure 1. The taxa extinction rate, major vulcanisms (uniformly shaded boxes) and episodes of mixed polarity of the Earth's magnetic field (hatched) plotted as functions of time for the recent Phanerozoic, the magnetic reversals between 50 and 250 Myr B.P. expanded to show correlation with the Permo-Triassic and Cretaceous-Tertiary boundaries.

Several propositions relating to cometary evolution are implicit in the CN scheme and are mentioned here as being critical to it in varying degrees. Thus it is assumed that:

1. Comets are natural primary condensations in molecular clouds (e.g. Greenberg 1974; Humphries 1982) although the condensation mechanism is not yet established (Clube 1982).

2. The flux of long period comets is consistent to order of magnitude with the Apollo asteroid population and with the average cratering rate over the last 3 Byr; but a precise balance is not expected (Shoemaker et al. 1979, Neukum et al. 1975);

3. The asteroid belt is not the dominant source of Apollo asteroids (Wetherill 1976); and in fact

4. The short period comets evolve rapidly to produce not only meteor streams and fireballs but also Apollo asteroids (Öpik 1961; Drummond 1982).

Although periodic replenishment of the comet cloud is in principle consistent with either inner cloud perturbation or external capture, the approximate constancy of the mean cratering rate during the last 3 Byr would require the inner cloud population to be not significantly depleted during the lifetime of the Solar System, and this in turn would require one to think in terms of a rather large primordial population, 10^{13} comets say, whose emplacement might present serious difficulties to theories of their origin. Indeed, such a theory, unless particularly contrived, would necessarily raise the population of interstellar comets generally and further enhance the probability of captured comets. Replenishment by capture from outside the Solar System, implying a reasonably constant galactic environment, is prima facie the more likely possibility.

The Need for Frequent Replenishment

In this section, we consider the cumulative effect of average star and molecular cloud encounters on the Oort cloud based on representative data for the solar neighbourhood. The calculations, necessarily schematic, are based on the usual impulse approximation but take no account of inevitable close encounters with occasional (stochastically distributed) slowly moving bodies which provide an additional and not insignificant source of Oort cloud energisation. We seek to determine whether the velocity dispersion added to typical Oort cloud members during the lifetime of the Solar System is greatly in excess of the usual escape velocity.

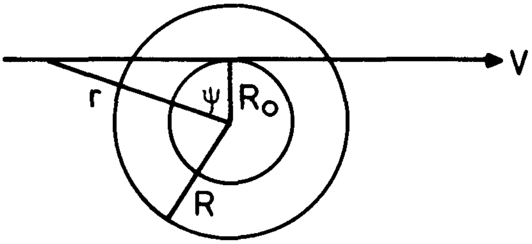

Figure 2. Impact geometry for idealized encounter with a molecular cloud (see text).

Consider a representative spherical molecular cloud (mass M) of uniform density and radius R which the Sun encounters with impact parameter R_o and relative velocity V (see Figure 2). The velocity impulse experienced by Oort cloud members is typically

$$\Delta V = 2\int_{0}^{\infty} \frac{\mu(r)}{r^2} \cos\psi \, dt$$

where $\mu(r) = GM, \ r > R$ for a fly-by encounter
$= GM(r/R)^3, \ r < R$ for a penetrating encounter

Therefore

$$\Delta V = (2GM/R_o V) \quad \text{(Fly-by)}$$
$$(2GM/R_o V)\ (1 - \sin^3\psi_o) \quad \text{(Penetration)}$$

where $\cos \psi_o = R_o/R$.

Following the methodology of Oort (1950), the energy fed to Oort Cloud comets as a result of penetrating and fly-by encounters is found to be

$$\sum_t \Delta V^2 = 2\pi(2GM)^2\ V^{-1}\nu t\ (a^2/R^2)\ (P + F)$$

where $P = \int_0^1 x^{-3}\ (1 - (1 - x^2)^{3/2})^2 dx = 0.81$

$F = \int_1^\infty x^{-3} dx = 0.5$

a = radius of the Oort Cloud

ν = number density of molecular clouds

t = age of the Solar System

and V^{-1} assumes a representative mean value characterising the velocity dispersion of encountering bodies and the Sun's velocity during the last 4.5 Byr. Some of these factors can only be assessed in an approximate way (e.g. CN, Bailey 1982) so we shall for simplicity follow the usual practice here and assume $V = 20$ kms^{-1} (e.g. Oort 1950). Thus, making suitable substitutions, we obtain

$$\sum_t \Delta V^2 = 740\ \nu\ M^2\ (a/R)^2 \times 10^8\ (\text{cms}^{-1})^2 \qquad (1)$$

where ν is in kpc^{-3} and M is in units of $2.21 \times 10^5 M_\odot$. For comparison we note the escape value for Oort cloud members at 50,000 a.u.:

$$V_E^2 = 3.6 \times 10^8 \qquad (\text{cms}^{-1})^2$$

The masses, number densities and distribution of molecular clouds are still much discussed in the literature (Solomon and Sanders 1980, Blitz 1981, Liszt et al. 1981) and our aim in seeking acceptable substitutions for equation (1) is, if we err, to err as far as possible on the conservative side. Treating the molecular cloud distribution as if it were gathered into giant molecular clouds of mass $2 \times 10^5 M_\odot$, the solar neighbourhood value of ν is $\sim$40 (thus, case I: $M = 0.9$, $a/R = 0.01$, $\nu = 40$) but it should be noted that a figure twice as large is implied for the past time-averaged local value of ν based on the local star formation rate, in broad agreement with stellar kinematic data (Wielen 1977). The value $\nu = 40$ corresponds to half a dozen penetrating encounters of GMCs in 4.5 Byr and, with the assumed dimensions, there would be produced a significant encounter with GMC substructure at each penetration. In order to assess the effects of substructure, we consider two extreme models within which the observed structure can be considered to lie: one with the substructure concentrated entirely in GMCs and the other with substructure uniformly distributed throughout the disc, that is, there are no GMCs. (Case II: M = 0.09, a/R = 0.05, ν = 400). It follows that for

Case I (GMCs) $\sum_t \Delta V_G^2 = 2.4 \times 10^8 \quad (\mathrm{cms}^{-1})^2$

Case II (substructure) $\sum_t \Delta V_S^2 = 6.0 \times 10^8 \quad (\mathrm{cms}^{-1})^2$

While stars, for comparison, produce

$$\sum_t \Delta V_*^2 = 2.6 \times 10^8 \quad (\mathrm{cms}^{-1})^2$$

The cumulative effect is therefore in the approximate range

$$8.6 \times 10^8 < \sum_t \Delta V^2 < 11.0 \times 10^8 \quad (\mathrm{cms}^{-1})^2$$

with $\sum \Delta V^2/V_E^2$ typically $\sim$ 3. These calculations relax some of the effects which were considered also to apply by Napier and Staniucha (e.g. gravitational focussing, lower velocity dispersion of GMCs, and a slightly flatter disc) which would result here in an increased ratio $\sum \Delta V^2/V_E^2 \sim 9$. Further increase of the ratio can be expected however to result from exceptional close encounters which in reality are likely to dominate the system. Also neglected in the calculation is the fact that a is not constant but tends statistically to increase. This too is a large effect since a single close encounter will generally substantially loosen the binding of surviving long period comets. In addition, the full escape value has to be achieved for disruption on the proto-planetary ejection hypothesis whereas on the Cameron or the capture hypothesis, the cloud is emplaced with a significant initial velocity dispersion. We conclude that the molecular cloud parameters which are currently preferred appear to render the Oort cloud (treated as a system of characteristic radius 50,000 a.u.) subject to inevitable disruption during the lifetime of the Solar System. If the observed cloud is typical of the average state of the Solar System, the need for replenishment has to be considered likewise inevitable.

Conclusion

In the current state of knowledge, it seems the primordial and recent capture hypotheses for the Oort cloud deserve at least equal consideration. The increased stature of the latter hypothesis does perhaps further highlight the importance of the currently unsolved problem of cometary growth in molecular clouds. It would seem now to be of fundamental importance to establish the correct physical relationship between interstellar dust, interplanetary dust and the most primitive carbonaceous chondritic material.

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DISCUSSION

DONN: Dr. Thaddeus (unpublished) claims an order of magnitude smaller molecular cloud frequency than the published values which he attributes to his nearly complete coverage of the Milky Way compared to the grid of points used in previous work.

CLUBE: I agree that this is an important point that needs to be resolved.

A'HEARN: Would not both stripping and replenishment of the Oort cloud by giant molecular clouds lead to significant asymmetries in the distribution of perihelion-aphelion directions which were produced sufficiently recently that they have not yet been randomized?

CLUBE: Although complete thermalization is, to first order at least, a common feature of Oort cloud theories, the observed asymmetries can in principle tell us about recent perturbations and may well be related to either depletion or replenishment mechanisms.

KOEBERL: If you assume that interstellar comets are the main source of Apollo asteroids giving rise to large craters on Earth, you would have a broad distribution of isotopic compositions of elements from different clouds, resulting from nucleosynthetic processes in stars. This is not observed.

CLUBE: I am not sure that anything relevant has yet been observed. In the first place, extraterrestrial material has not been detected in about 90 % of craters, possibly because the undifferentiated cometary material responsible for the craters is diluted by (varying) large amounts of terrestrial material. To add to the confusion, the latest evidence suggests the $^{12}C/^{13}C$ ratio in the densest parts of molecular clouds, where comets are most likely formed, is very close to the terrestrial value. This incidentally, is not easily explained on current nucleosynthesis scenarios.