MOLECULAR CLOUDS: COMET FACTORIES?

S.V.M. Clube
Department of Astrophysics,
South Parks Road, Oxford OX1 3RQ

ABSTRACT. Recent discoveries seem to indicate a catastrophic history of terrestrial evolution, explicable in terms of Oort cloud disturbance by molecular clouds in the Galactic disc. The problem of Oort cloud replenishment thus assumes considerable significance and reasons are given for supposing comet exchange takes place during actual penetration of molecular clouds. The number density of comets in molecular clouds, thereby implied, seems to suggest primary condensations of $\lesssim 10^3$km in a dense precursor state of spiral arms. If chemical and/or isotopic signatures of comets should indicate an extra-Solar System source, the theory of terrestrial catastrophism may place new constraints on our understanding of the origin of molecular clouds.

INTRODUCTION

That the Galaxy may influence the Earth is a comparatively old idea. Cycles of some 200-250 Myr and some 30 Myr for example were noted in the terrestrial record at least fifty years ago (e.g. Holmes 1927) and because no earthbound engine operating at these frequencies was known, the possibility of Galactic control became a subject for speculation. Thus, the Sun's motion relative to the underlying Galactic substratum, $[(\Pi_0 - \Pi_G), (\Theta_0 - \Theta_G), (Z_0 - Z_G)] \approx [10, 15, 7]$ kms^{-1}, happens to combine with the above periods to produce characteristic displacements parallel and perpendicular to the plane of $\sim$5000 pc and $\sim$200 pc respectively. These are not very different from the separation and thickness of spiral arms, the separation here being a rough average of the radial and tangential values. That something in spiral arms might affect the Earth seemed a reasonable possibility therefore, and it is understandable that speculations should have arisen linking interstellar clouds with ice ages for example, or supernovae with extinctions (McCrea 1981). About ten years ago however, the Galaxy's massive molecular cloud system was detected (Gordon and Burton 1980, Solomon and Sanders 1980) and planetary scientists were meanwhile demonstrating a likely connection between the Apollo asteroid system and the continuous

A. Carusi and G. B. Valsecchi (eds.), Dynamics of Comets: Their Origin and Evolution, 19–30.

cratering record (Shoemaker et al 1979). Now, it had already been recognized that long period comets that were not deflected by planetary perturbations out of the Solar System altogether may be the principal source of short period comets and thus, in devolatilised form, of Apollo asteroids (Opik 1961), so it was possible that the Oort cloud was being regularly perturbed by molecular clouds in spiral arms and that corresponding enhancements in the flux of live and dead comets were directly responsible for the episodic terrestrial record, controlling both ice-ages and extinctions, as well as major orogenic cycles and the fluctuating pattern of magnetic reversals (Clube 1978; Napier and Clube 1979; cf Clube and Napier 1984a,b and references therein). In adopting this picture, the assumption that the asteroid belt was a principal source of Apollos had of course to be abandoned, there being no known mechanism in this case permitting Galactic periodicities.

Until this time, the Oort cloud had been considered to play a comparatively passive role in Solar System history, being supposedly perturbed only rather gently by passing stars, but it had also become clear that this picture might be in need of revision. Thus, neither the perihelion distribution of the long-period comet system nor its orbital energy distribution appeared to be in a relaxed state; moreover, dynamical simulations of Jupiter's role in transferring long-period comets to the short-period population seemed to suggest the latter was too large, indicating perhaps a recent surge in the long-period comet flux. Admittedly, passing stars might explain the perihelion distribution (but see Yabushita : these proceedings), fading might explain the orbital energy distribution (see Bailey: these proceedings), and an arbitrary comet cloud beyond Saturn might be invoked to explain the short-period comets (e.g. Fernandez & Jockers 1983), but there was also obvious attraction in a proposal that attributed to all three the same cause. Thus, given (1) the relative proximity of the molecular clouds in Gould's Belt through which the Sun had just passed, and (2) the many indications that the Earth is currently immersed in an extended period ($\gtrsim$3 Myr) of generally high glacial, magnetic and orogenic activity, these signs of recent Oort cloud disturbance were not inconsistent with the general proposition.

The credibility of theories involving comet-induced terrestrial catastrophism was considerably enhanced by the discovery of excess iridium at the Cretaceous-Tertiary boundary suggestive of extra-terrestrial input (Alvarez 1983) but later work showed the concentration of such material was too large to be explicable in terms of impact alone (Kyte and Wasson 1984) even though quartz crystals with impact signatures were evidently present (Bohor et al 1984). In addition, a similar iridium enhanced layer at the Eocene-Oligocene boundary did not coincide exactly with the microtektite layer which is thought to be impact induced and to correlate with the corresponding extinction (Kyte et al 1981); thus, Δt was found to be $\sim$0.03 Myr. If such theories were to be relied upon therefore, it was apparent that processes of some complexity were at play involving the direct deposition of cosmic dust as well as impacts.

To meet the facts therefore, we may envisage the following sequence of events: during its journey through the Galaxy, the Solar System experiences successive close passages by molecular clouds, of relatively short duration (~0.25 Myr), the effect on the orbit of a typical comet in the Oort cloud each time being that of a simple random impulse (Clube & Napier 1983). Each passage results in a cascade of comets into the Solar System which lasts typically half an orbital period (i.e ~2 Myr) thereby replenishing the short and intermediate period comet population from which a small fraction diffuses over the subsequent ~5 Myr into orbits of the Apollo-Amor kind (Rickman and Froeschlé 1980). On entering these relatively more stable orbits, the physical evolution and disintegration of each successive comet proceeds rather rapidly, probably with a spell of continuous devolatilisation that is strongest during the first $\sim 10^2 - 10^3$ perihelion passages, followed by a period of more intermittent fragmentation, each producing either continuous or intermittent dust in orbit that feeds into a contemporary zodiacal cloud. Since the mass spectrum of comets (eg Hughes and Daniels 1982) is such that the very largest bodies contain most of the mass, we can expect the evolution of Chiron-like bodies ($\gtrsim$100 km) arriving at ~0.1 Myr intervals to dominate the inner region of the Solar System i.e. the zone bounded by the Jovian orbit. How the evolution proceeds obviously depends on the structure and composition of large comets : 'dirty snowballs' accreted in a cold environment would probably simply disintegrate into dust and gas but if gravitational or radioactive heating occurs during formation, with differentiation we can also expect more solid remnants. The stream of disintegration products (dust, boulders, Apollo asteroids) associated with each of these particular bodies is thus largely responsible for the course of terrestrial evolution. Indeed, each giant comet tends to produce a recurring dust veil on Earth of generally diminishing intensity, resulting probably in a major glaciation followed by a sequence of climatic recessions interspersed with the effects of an occasional asteroidal impact, all within a period of ~0.01 - 0.1 Myr (Clube and Napier 1984b). The effect of a single molecular cloud passage is thus an episode of glaciations possibly correlated with magnetic reversals (Doake 1978), at ~0.1 - 1.0 Myr intervals lasting $\gtrsim$5 Myr during which the largest asteroid encounter can result in a single major extinction. Now, at the present time, the terrestrial planets appear to be swept twice a year by the broad Taurid-Arietid streams of dust (Stohl 1983) and boulders (Dorman et al 1978) produced during past fragmentations of the Comet Encke progenitor (Whipple and Hamid 1952), whilst cosmic dust extracted from the late Pleistocene ice (LaViolette 1983, 1984) and debris scattered by the more recent Tunguska missile (Ganapathy 1983; Golenetskii _et al_ 1981) appear to have remarkably similar, yet anomalous, chemical signatures, iridium in particular being well above the normal terrestrial level (see Figures 1 and 2). The evidence therefore suggests a single disintegrating giant comet which first gave rise to the last ice-age on entry into the sub-Jovian region ~0.02 Myr ago, and then later

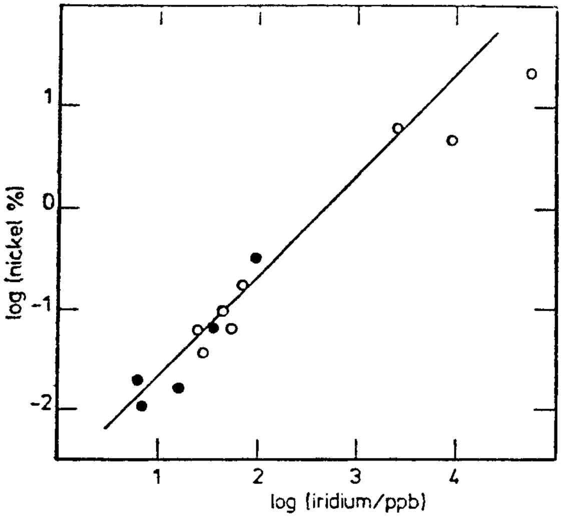

Figure 1
The nickel-iridium ratio for dust in the Camp Century ice-core covering the period 19,700-14,200 BP (filled circles) and from microparticles discovered at the site of the 1908 AD Tunguska explosion. The solid line represents a 'cosmic' abundance ratio but according to Ganapathy (1983), randomly selected meteor ablation products show a very large scatter (~1 dex) about this line. The good fit of both sources to this line seems therefore to imply a single progenitor body, especially if the common anomalies are also taken into consideration (see Figure 2).

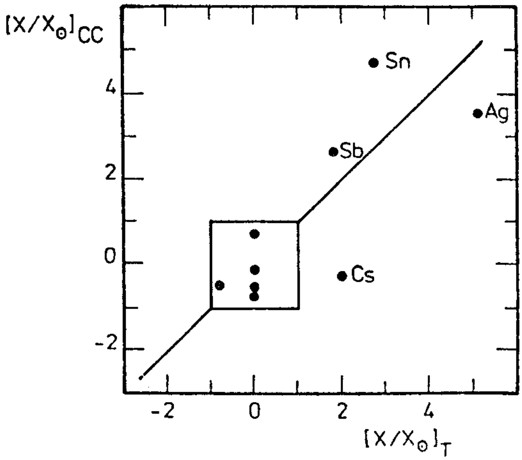

Figure 2
Log-log plot of abundances relative to CI for various elements detected in Camp Century polar ice and the Tunguska fallout. The error box centred on 0,0 is expected to take in all elements displaying normal chondritic abundance while the 45° line is that corresponding to identical anomalies. There appears to be a common trend in the anomalies, tin and silver being significantly overabundant by a factor ~10^4.

left a devolatilised core which is probably still circulating in the Taurid stream, possibly the source of the prominent boulder swarm encountered by the Moon in June 1975 (Dorman et al 1978) as well as the Tunguska missile and the current zodiacal cloud. The existence of the devolatilised body remains of course to be verified but it seems reasonable to assume the recent events and the immediate state of the sub-Jovian region closely replicate the circumstances producing the most active periods in the terrestrial record i.e. the effects that have followed our recent passage through Gould's Belt simply typify the Solar System's past interaction with molecular clouds in the Galactic disc.

Although, on the above chain of argument, molecular clouds are believed to play a dominant role in Earth history, many aspects of the thesis remain to be examined in detail and one cannot yet be certain as to its validity. Nevertheless, it is difficult on present evidence to see how it can be excluded; past encounters with dead comets and their debris may therefore be leaving a significant record of interaction with the Galaxy on Earth which can have new, far-reaching consequences for our understanding of the Galaxy. In this paper, the immediate aim is to review some possible implications as far as the molecular cloud system is concerned.

INNER CLOUD OR CAPTURE?

Although the current long-period and short-period comet systems together with the terrestrial record through the last few million years are now taken to characterise transient states of the Solar System following molecular cloud passages, it is clear in principle that the ~10-20 most energetic encounters during the lifetime of the Solar System, possibly involving actual penetration of GMCs, should have dispersed the Oort cloud altogether (Clube and Napier 1983). It is necessary therefore to consider how the latter may have been replenished. Two main suggestions have been made: (1) that there exists an inner cloud ~10^3 a.u. in size releasing comets into the Oort cloud by the action of the very same molecular cloud perturbations that cause the latter to be removed and (2) that comets are occasionally captured from dense star-forming regions in the molecular clouds themselves.

The extent of any postulated inner cloud could reflect primordial conditions (e.g. Bailey 1983, Hills 1981) or it may be that it is regularly replenished itself by planetary perturbations from an even more tightly bound Uranus-Neptune cloud (Shoemaker and Wolfe 1984). In either case, however, there is a potential difficulty. Thus, any process replenishing the Oort cloud from further in is likely to be inefficient (say a few percent) since a relatively small excess energy imparted by molecular clouds will take comet orbits not only beyond the Oort cloud but outside the solar sphere of influence altogether. It follows that a typical Oort cloud replenishment involving ~10^{11} comets may require ~10^{13} comets to be drawn from the inner cloud. And if there are ~10 typical penetrations of GMCs during the lifetime of the Solar System producing major replenishments of the Oort cloud without significant depletion of the parent source (which is necessary to be consistent with the approximately constant cratering rate), then an inner cloud, or Uranus-Neptune cloud, of $\gtrsim 10^{15}$ comets may have to be envisaged. There has as yet been no detailed modelling of this process but with typical cometary masses $\sim 10^{17}$ gm, it is possible that an inner cloud of $\gtrsim 0.1 M_{\odot}$ may be required. Indeed, if the formative material is drawn from a medium of $\sim$ solar abundance, a primordial Solar System of $\gtrsim 10 M_{\odot}$ could well be necessary, not in very satisfactory agreement with the rough balance of mass between recently formed stars and the amount of material in molecular clouds.

Although these arguments are not definitive, the inner cloud hypothesis appears to have drawbacks: it is necessary therefore to consider the capture hypothesis (Clube and Napier 1984a). In the past, comet capture from the interstellar medium has usually been regarded as inherently unlikely due to the relatively high velocity ($\sim$ 20 kms^{-1}) of the Sun and such limits as are placed on the space density of interstellar comets by the lack of observed hyperbolic candidates travelling through the Solar System. The problem cannot be resolved by simply postulating a high space density of comets in molecular clouds for such comets would, like stars, eventually dissipate into the Galactic disc, and the detection limit for hyperbolic comets also places a constraint on the possible number of comets in previous generations of molecular clouds - always assuming of course that comets survive virtually intact at their expected average distance from radiating sources. However, one possible combination of factors has been overlooked, namely the fluctuating gravitational potential inherent in the hierarchical structure of molecular clouds, and the gradual enlargement of the solar sphere of influence as the Sun climbs out of the potential well associated with a GMC. The result under these circumstances is that a comet entering the solar sphere of influence at above the escape velocity during molecular cloud passage can subsequently experience a random set of perturbations which cause it later to arrive at the enlarged sphere of influence with less than the escape velocity and thus be captured. Quantitatively, this implies that a much larger volume of velocity space relative to the Sun than has been previously considered possible is in fact available for capture. The corollary is that a typical family of $\sim 10^{11}$ comets in orbits like those associated with the Oort cloud can be captured by the Sun during GMC penetrations if a comet population of mean density ~ 0.1 a.u.$^{-3}$ is assumed to be present (Clube and Napier 1984a). There is perhaps order of magnitude uncertainty in this figure depending on the precise motion of the Sun through the GMC and the distribution of material throughout the cloud. Nevertheless, if such a figure be adopted generally for GMCs throughout Galactic history, the implicit number of comets in the disc is then consistent with the observed limit based on the lack of hyperbolic comets in the Solar System (Sekanina 1976). It thus seems that terrestrial history and the current state of the comet population attached to the Sun are in principle explained if GMCs generally contain comets at the above space density. Even though such comets will probably be undetectable in situ, the inference can hardly be disallowed a priori since GMCs house star-forming regions and comets are usually assumed to be formed along with stars. The space density is at first sight a rather inconsequential result, but there are further possible implications concerning the properties of molecular clouds, particularly their role as comet factories.

THE HIGH NUMBER DENSITY OF COMETS IN GMCs

The number density implies the observed molecular hydrogen in a GMC in combination with its comets gives a roughly solar mix, whilst the amount of high Z material in comets (i.e. $Z>2$) is evidently comparable to that in stars, even to the extent that most of the high Z material in GMCs may at some stage reside in comets. An extremely efficient mode of comet formation seems to be indicated therefore, but if it occurs more or less randomly throughout molecular clouds by sedimentation say (McCrea and Williams 1965) or by the action of differential radiation pressure for example (Hills 1982), some additional (unknown) method of gathering together preformed planetesimals with the appropriate proportion of gas would have to be invoked to make stars. In practice, random comets would be expected to disperse into the Galactic disc, as do stars, thus comets captured from GMCs seem more likely to have emerged from preformed dense star-forming regions, consistent with generally accepted ideas regarding Sun and planet cosmogony. However, the very large mass of comets escaping from such regions within GMCs would have to imply compact but nevertheless very loosely bound (i.e non-virialised) aggregates, not unlike the assemblies of supersonic floccules proposed by McCrea (1978) as the starting point of star formation. Under these circumstances, with comets preformed, we might expect to see element deficiencies relative to solar abundance in the interstellar medium which increase strongly with hydrogen column density in star-forming regions, and such an effect is in fact observed (Cardelli and Bohm-Vitense 1982; Phillips et al 1982; Mentense 1982; Tarafdar 1983). These large Z depletions are already a problem for current theories of stellar collapse for if hydrodynamic or magnetohydrodynamic forces control the gas and purely ballistic ones control the comets, it is not clear how stars of roughly normal abundance can arise from a gas that is strongly depleted of its high Z component. Again, it seems more reasonable to treat the dense concentrations as dissipating regions with comets and gas emerging together from a pre-stellar compact state of near zero energy. The assumption that comets are stellar precursors is however contrary to the current orthodoxy.

Both the large Z depletions in the densest regions of molecular clouds and the possible existence of captured comets seem then to be indicating a very dense starting point for star formation which is not initially self-gravitating (i.e. not virialised) and whose initial condensations are ultimately of cometary dimensions. Conceivably though, most observed comets are fragments of these primary condensations, in which case the initial bodies would correspond to the largest observed comets or their 'volatilised' counterparts of approximately solar abundance. Such bodies would have mass $\lesssim 10^{24}$ gm (dimensions $\lesssim 10^{3}$ km.) and are likely to have cores that have experienced some degree of differentiation. Thus, dense non-virialized systems have short survival times and one expects the primary bodies to have undergone some internal heating if the final stage of their formation involves relatively rapid gravitational collapse. Meteoriticists often favour primary bodies of this character (Grossman and Larimer 1974) and it has been known for some time of course that there is advantage in making planetesimals first since this would in principle resolve the angular momentum problem of Solar System (and star) formation (McCrea 1978; Woolfson 1979). Moreover, if aggregates of such bodies are supersonic as well as being dense, as McCrea has envisaged, we might expect any virialised disc that forms along with a centrally condensed star will be associated with the escape of a comparable mass of material which is likely to be most clearly seen where it is unimpeded by the primordial disc. Roughly symmetrical bipolar outflows are thus a reasonable expectation, and it may be significant that bipolar flows are probably associated with the making of all stars (Lada 1983). Now, it would be premature to suggest the argument developed here is necessarily unique but there does seem to be a reasonably supported line of evidence based on the 'observed' number density of comets in GMCs, indicating that the first stage in making stars might be the formation of $\sim 10^{24}$ gm bodies in a medium of $\sim$ solar abundance which is necessarily very dense. Neither the process of coagulation nor the pressure under which such bodies would form are of course known at present, but if the trigger is pressure alone, it is even possible the primary condensations precipitate from the compressed medium as simple gravitational instabilities. Thus, the picture that seems to emerge is of the interstellar medium being rather rapidly compressed to produce the primary condensations, half then combining to produce stars and planets, whilst the remainder devolatilise to produce comets and molecular clouds. Any gain in simplicity such a picture might bring would clearly be offset by the problem of identifying the apparently non-gravitational process that induces the necessary compression. Nevertheless, if future studies of cometary material should indicate that it is indeed captured from outside the Solar System, significant new insights into the processes leading to the formation of comets and molecular clouds in spiral arms may be at hand: understanding terrestrial catastrophism can thus in principle influence our understanding of the way the Galaxy works.

INTERSTELLAR COMETS?

Cometary material, as distinct from meteorites which have been more extensively studied, currently deposits on Earth in the form of micrometeorites. These are irregularly shaped interplanetary dust particles with dimensions up to a few hundred microns, many in the form of low density, so-called Brownlee particles composed of submicron size dust grains embedded together in a fragile, porous matrix with flat 'plate-like' or 'whisker-like' crystals of larger size which probably formed by gas-to-particle condensation from a low-pressure hot vapour phase (Bradley et al 1983). Included also in the extra-terrestrial input are small spherical bodies which seem to be micrometeorites that have been heated to a molten state before entering the Earth's atmosphere (Parkin et al 1977): they have been detected in the stratosphere, ocean sediments, glacial ice, lunar soil and as 'chondrules' in chondritic meteorites. Besides exhibiting normal chondritic elemental signatures, many of these microspheres have highly anomalous compositions. There are instances for example where calcium, aluminium and titanium are exceptionally concentrated but in other cases, other elements may be greatly enriched. In general then, the micrometeoritic material deposited on the Earth during the last 20,000 years may be attributed to a relatively steady flux of disintegrating comets that underwent various degrees of differentiation during formation.

Many of the centimetre-sized primitive chondritic inclusions in the Allende meteorite are also rich in Ca-Al-Ti and it has been suggested that such excesses may have a similar explanation to that of micrometeorites (LaViolette 1983). So far as the Allende meteorite is concerned, the inclusions are thought also to contain material preserved from the earliest stages of Solar System condensation, revealing contamination from a (possibly nearby) exotic source such as a supernova (Wasserburg and Papanastassiou 1982; however cf Clayton 1984). Since comets are generally supposed to be among the most primitive of bodies, it would perhaps not be unexpected if they too displayed contamination of a similar kind. The cosmic dust deposited in glacial ice does indeed carry plate-like particles of anomalous composition which physically resemble the (enstatite) crystal platelets found in Brownlee particles (LaViolette 1983). The possibility arises therefore that different comets bear different signatures reflecting their particular condensation and contamination histories. It follows that material from comets from inside or outside the Solar System will not necessarily display identical chemical signatures. The similarly tin-rich chondritic dust discovered in abundance in the Camp Century late Pleistocene ice and in the Tunguska fallout is thus probably indicative of a single common source (ie a giant comet) which may or may not be from outside the Solar System.

It has been shown by Kyte et al (1983) that rather similar considerations apply to cosmic material deposited at the Cretaceous-Tertiary boundary. The abundance pattern in this case resembles a Solar System source very closely but it does not fit known meteorite types: thus, there is significant enrichment of Os, Re and other elements relative to chondritic meteorites or irons. Isotope anomalies moreover, have been detected in the material at this boundary, such as $^{187}Os/^{186}Os$ (Luck and Turekian 1983) and $^{12}C/^{13}C$

(Bonté *et al* 1984) and these are at least suggestive of a non-Solar System source. Whilst the origin of the chemical and isotopic anomalies in cometary material has not been settled, and until suitable isotope age indicators have been developed, one cannot say with certainty whether these data imply a non-Solar System source for (live or dead) comets striking the Earth. Nevertheless, the balance of evidence may now be favouring an interstellar origin.

CONCLUSIONS

It is possible the discovery of molecular clouds in the Galaxy, combined with recent cometary studies and the terrestrial record, leads now to a very specific picture of star formation in which the primary process is one of very rapid compression of the interstellar medium. Spiral arms initially composed of comets are thus implied which, contrary to a common view, are themselves the dissipating source of molecular clouds. Molecular clouds are then unlikely to be comet factories.

REFERENCES

Alvarez, L.W. 1983 Proc. Natl. Acad. Sci USA 80, 627.
Bailey, M.E. 1983 Mon. Not. R. astr. Soc. 202, 603.
Bohor, B.F., Foord, E.E., Modreski, P.J. & Triplehorn, D.M. 1984 Science 224, 867.
Bonté, Ph., Delacotte, O., Renard, M., Laj, C., Boclet, D., Jehanno, C., & Rocchia, R. 1984 Geophys. Res. Lettr. 11, 473.
Bradley, J.P., Brownlee, D.E. & Veblen, D.R. 1983. Nature 301, 473.
Cardelli, J. & Böhm-Vitense, E. 1982. Astrophys J. 262, 213.
Clayton, D.D. 1984 Astrophys. J. 280, 144.
Clube, S.V.M. 1978 Vistas in Astronomy 22, 77.
Clube, S.V.M. & Napier, W.M. 1983 Highlights of Astronomy 6, 355.
Clube, S.V.M. & Napier, W.M. 1984a. Mon.Not.R.astr.Soc. 208, 575.
Clube, S.V.M. & Napier, W.M. 1984b. Mon. Not. R. astr. Soc. in press.
Doake, C.S.M. 1978 Earth Planet. Sci. Lett. 38, 313.
Dorman, J., Evans, S., Nakamura, Y. & Latham, G. 1978 Proc. Lunar Planet Sci Conf 9, 3615.

Fernandez, J.A. & Jockers, K. 1983 Rep. Prog. Phys. 46, 665.
Ganapathy, R. 1983 Science 220, 1158.
Golenetskii, S.P., Stepanok, V.V. & Murashov, D.A. 1982 Translated from Astr. Vestu. 15, 167, 1981.
Gordon, M.A. and Burton, W.B. 1980 Proc. Third Gregynog Astrophysics Workshop on Giant Molecular Clouds (ed. Solomon et al) 25.
Grossman, L. & Larimer, L. 1974 Rev. Geophys. Space Phys. 12, 71.
Hills, G.J. 1981 Astron. J. 86, 1730.
Hills, G.J. 1982 Astron. J. 87, 906.
Holmes, A. 1927 The age of the Earth - An Introduction to Geological Ideas (Benn, London).
Hughes, D.W. & Daniels, P.A. 1982 Mon. Not. R. astr. Soc. 198, 573.
Kyte, F.T. & Zhou, Z., 1980 Meteoritics 15, 320.
Kyte, F.T., Zhou, Z. & Wasson, J.T. 1981 Nature 292, 417.
Kyte, F.T. & Wasson, J.T. 1984 Meteoritics 19, 332.
Lada, C.J. 1983 Star Formation Workshop (Royal Observatory, Edinburgh), in press.
LaViolette, P. 1983 Thesis, Portland State University.
LaViolette, P. 1984 Evidence of High Cosmic Dust Concentrations in Late Pleistocene Polar Ice (20,000-14,000 years B.P.), submitted.
Luck, J.M. & Turekian, K.K. 1983 Science 219, 613.
McCrea W.H. 1978 In 'The Origin of the Solar System' (ed. Dermott), 75.
McCrea, W.H. 1981 Proc. R. Soc. London A375, 1.
McCrea, W.H. & Williams, I.P. 1965 Proc. R. Soc. London A287, 143.
Mentense, H.H. 1982 Astrophys Space Sci 82, 173.
Napier, W.M. & Clube, S.V.M. 1979 Nature 282, 455.
Opik, E.J. 1961 Adv. Astro. Astrophys. 2, 219.
Parkin, D.W., Sullivan, R.A.L. & Andrews, J.N. 1977 Nature 266, 515.
Phillips, A.P., Gondhalekar, P.M. & Pettini, M. 1982 Mon. Not. R. astr. Soc. 200, 687.
Rickman, H. & Froeschlé, C. 1980 Moon and Planets 22, 125.
Sekanina, Z. 1976 Icarus 27, 123.
Shoemaker, E.M., Williams, J.G. Helin, E.F. and Wolfe, R.F. 1979 In Asteroids (ed: Gehrels), 253.
Shoemaker, E.M. & Wolfe, R.F. 1984 Meteoritical Society, abstract submitted.
Solomon, P.M. & Sanders, S.B. 1980 In Proc. Third Gregynog Astrophysics Workshop on Giant Molecular Clouds (ed: Solomon), 41.
Stohl, J. 1983 In Asteroids, Comets, Meteors (ed: Lagerkvist & Richman, Uppsala), 419.
Tarafdar, S.P., Prasad, S.S. & Huntress, W.T. 1983 Astrophys. J. 267, 156.
Wasserburg, G.J. & Papanastassiou, D.A. 1982 In 'Essays in Nuclear Astrophysics" (ed: Barnes), 77.
Whipple, F.L. & Hamid, S.E. 1952 Hellwan Obs. Bull. 41, 1.
Woolfson, M.N. 1979 Quart. J.R. astr. Soc. 20, 97.

DISCUSSION

Yabushita: You mention Jeans' gravitational instability as a mechanism of cometary formation. I think sedimentation is a more natural process.

Clube: You may be correct though on the picture I have been discussing, the formation of regions of high density would still be expected to precede the sedimentation.

Fernandez: For a capture event ~5 Myr ago, you might expect an increase of the comet bombardment of the terrestrial planets during the last few million years. Is there any evidence in the cratering record of the Earth in support of this view?

Clube: Precipitation may cause large craters formed more than about 1 Myr ago to be deeply eroded or filled by sediments whilst in areas of glaciation, they may be completely obliterated. Detailed geological mapping of the Earth's surface is also incomplete, so it is unlikely that all young continental impact structures greater than, say, 18 km have been recognized (Shoemaker, Ann. Rev. Earth Planet Sci. 11, 461, 1983). Nevertheless, based on the current asteroid population, which the theory requires to be on the order of the time-averaged population through the Phanerozoic, there is a 99% probability of at least one 18 km crater within the last 3.5 Myr. One such crater is known (Lake Elgygytgyn, Eastern Siberia) with a K/Ar age of 3.5±0.5 Myr.

Delsemme: The periodicity of mass extinctions of species on Earth (~30 Myr) does not seem to fit in with the periodicity of molecular cloud collisions with the Solar System. What do we know about molecular cloud statistics?

Clube: Although a very unlikely companion star hypothesis has been put forward, the ~30 Myr cycle probably relates to the Sun's galactic z-motion and implies a rather high frequency of molecular cloud encounters. Our knowlege of the statistics and the Sun's past motion is not sufficient at present to exclude the z-motion hypothesis.