DYNAMICAL INTERACTIONS OF THE SOLAR SYSTEM WITH MASSIVE NEBULAE

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ABSTRACT

The effects of encounters with massive nebulae on the long-period comet population are examined, paying particular attention to the uncertainties in the data. An earlier conclusion, that the long-period comet system is dynamically unstable, is upheld. Whether replenishment by unbinding from a dense inner comet cloud is a viable hypothesis awaits detailed modelling, but a qualitative discussion is given which argues tentatively against it. If comets occur in molecular clouds, however, their capture into temporarily bound Solar System orbits is a natural consequence of close encounters for realistic velocities and potentials. A large disturbance or capture may have occurred a few Myr ago as the Sun emerged from the Orion spiral arm.

INTRODUCTION

In a series of papers (Napier & Clube 1979; Napier & Staniucha 1982; Clube & Napier 1982a, 1983, 1984a; Bailey 1983) it has been argued that the long-period comet system is likely to be dynamically unstable, because of the tidal action of molecular clouds, and must therefore be replenished from elsewhere. Such replenishment might come from a hypothetical dense inner cloud of comets, by capture of comets from the molecular clouds themselves, or from some combination. It has been stated (but not so far demonstrated: Weissman 1983, Dr. Fernandez, these proceedings) that the properties of molecular clouds are so uncertain that the issue of Oort cloud stability cannot be advanced beyond the speculative stage; therefore in this contribution I examine the question taking account as far as possible of the assumptions and uncertainties in the data. In particular the problem is formulated in such a way as to bring out the dependence on such factors as the adopted mass distribution of the nebulae, the local column density, gravitational focussing and so on.

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ADOPTED PROPERTIES OF THE MOLECULAR CLOUD SYSTEM

Early surveys of the CO emission in the galactic plane (Solomon & Sanders 1975, Gordon & Burton 1976) led to the discovery that much of the mass of the interstellar medium is in the form of molecular hydrogen concentrated into cold, massive nebulae. Initially there was much uncertainty about the mass and structure of the system, arising partly from uncertainties in the scaling factor between CO and H_2, partly from crowding effects in the inner regions of the Galaxy, and partly because of ambiguities in the kinematic distances of the nebulae. Thus while Solomon, Sanders & Scoville (S^3 1979) considered that most of the CO emission derived from giant molecular clouds (GMCs) of radii ~20 pc and masses ~5×10^5 $M_\odot$, Gordon & Burton (1980) modelled the CO emission by a more numerous population of clouds with masses $\gtrsim$ a few $10^4 M_\odot$ and radii ~2 - 10 pc. However the latter authors found a striking tendency for these clouds to occur in clusters, and the GMCs of S^3 show considerable substructure. It appears now that the difference was semantic (Liszt et al. 1981) and that there is essentially agreement between all groups that most of the mass and volume of H_2 does reside in very large sources.

More recently, CO observations covering galactic longitude -4° to 170° have been carried out by S^3 (1984), who also discuss the conversion factor between integrated CO intensity W_{CO} and the mass column density $N(H_2)$ of molecular hydrogen. They adopt $N(H_2)/W_{CO}$ = 3.6×10^{20} $cm^{-2}/(K\ cm\ s^{-1})$ and point out that all values now in use are within a factor 2 of this. Empirical measures of the factor yield ~$4 \pm 2 \times 10^{20}$ $cm^{-2}/(K\ cm\ s^{-1})$. From this it is found that within 16 kpc of the galactic centre, the total mass of H_2 is 3.5×10^9 $M_\odot$. Their study confirms that the emission is concentrated into GMCs with diameters 20-80 pc and masses 10^5 - 3×10^6 $M_\odot$. They find also that at the solar distance the molecular cloud surface density is 5.2 $M_\odot$ pc^{-2} measured in a column perpendicular to the galactic plane. The scale height of the system appears to be $Z_{1/2}$ ~75 pc as measured by CO emission, or ~50-60 pc if it is delineated by OB associations.

A mass spectrum has been derived for molecular clouds, of the form

$$n(m) = km^{-\alpha} \qquad (1)$$

where n(m) dm represents the number of molecular clouds per cubic kiloparsec in the mass range (m,m+dm) solar masses. The population index $\alpha = 1.45 \pm 0.08$ according to Thaddeus & Dame (1983), and that found by Xiang et al. (1984) can be fitted by $\alpha = 1.65 \pm 0.2$ or so. The distribution applies at least to masses $\gtrsim$ few 10^3 $M_\odot$, and is such that the bulk of the mass resides in the few largest clouds. Bhatt et al (1984), in a discussion of Lynds dark nebulae in the general field and the Taurus cloud complex, find $\alpha = 1.5 \pm 0.15$, but it is interesting that within the Orion and ρ Ophiuchus complexes

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the index is near unity. Drapatz & Zinnecker (1984) find a somewhat more complex mass distribution which, however, is in general accord with the power law spectrum for masses $\gtrsim 3 \times 10^3$ $M_\odot$.

According to Xiang et al (1984) molecular cloud radii are in the range $8 \lesssim R \lesssim 30$ pc, with mean ~ 13 pc. However the maximum contribution to the mass of the system comes from clouds with a mass of 8×10^5 $M_\odot$ whose radii are 20 pc.

Whether molecular clouds delineate spiral structure in the inner Galaxy is a controversial question but not crucial to the present analysis. Towards the outer Galaxy, where individual clouds are more easily defined, the Local, Perseus and Sagittarius arms are delineated by molecular clouds (Thaddeus & Dame 1984), Cohen et al (1980) finding that the arm/interarm contrast is $\gtrsim$ 5:1 around the Perseus Arm. It is suggested (Drapatz & Zinnecker 1984) that clouds with R<15 pc occur in arm and interarm regions, larger ones outlining, more or less, spiral structure.

PERTURBATION OF THE OORT CLOUD

It is convenient to divide encounters of the Solar System with molecular clouds into those with impact parameters p>20 pc and those with p<20 pc, referring to the latter as 'close encounters'. Many of the passages with p>20pc will be 'flybys', whereas many close encounters will involve actual penetration of GMCs. Assuming the mean peculiar velocity of the Sun over its history has been V = 20 km s^{-1}, the volume swept out within 20 pc of the Sun over 4500 Myr is ~ 0.11 kpc^3, whence the number of close encounters with GMCs having masses $\geq$m is

$$N(\geq m) = 0.11\ \nu(\geq m) \qquad (2)$$

$\nu(\geq m)$ representing the number density of molecular clouds with masses $\geq$m solar masses. It is measured in numbers kpc^{-3} and is given by

$$\nu(\geq m) = \left(\frac{2-\alpha}{\alpha-1}\right) \left(f^{\alpha-1}-1\right) \frac{\rho}{m_2} \qquad (3)$$

defining $f = m_2/m$. It is assumed that the mass spectrum (1) applies between lower and upper limits (m_1, m_2) respectively. ρ ($M_\odot$ kpc^{-3}) is the density of molecular cloud material at the solar distance. Adopting $\alpha = 1.5$, we have that

$$\nu(\geq m) = \frac{\rho}{m_2} \left(f^{1/2} - 1\right) \qquad (4)$$

If instead of a finite mass distribution it is assumed that all GMCs are of the same mass $\bar{m}$, one finds

$$\nu = \rho/\bar{m} \qquad (5)$$

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The density $\rho(M_\odot\ kpc^{-3})$ can be found in terms of the surface density $s(M_\odot\ pc^{-2})$ and total effective disc thickness h(pc) through

$$\rho = 10^9 \frac{s}{h} \qquad (6)$$

Hence for $s = 5\ M_\odot\ pc^{-2}$, $h = 100$ pc, $m_2 = 3 \times 10^6\ M_\odot$, one finds $\rho = 5 \times 10^7\ M_\odot\ kpc^{-3}$ and

$$\nu\ (>m) = 16.7\ (f^{1/2} - 1) \qquad (7)$$

which, with (2), yields

$$N(>m) = 1.8\ (f^{1/2} - 1) \qquad (8)$$

With these formulae, one find that there are

$\nu = 511\ kpc^{-3}$ clouds of mass $m_1 > 3 \times 10^3\ M_\odot$ yielding N = 56 close encounters,
75 kpc^{-3} clouds of mass $m_1 > 10^5\ M_\odot$ yielding 8.2 close encounters, and
24 kpc^{-3} clouds of mass $m_1 > 5 \times 10^5\ M_\odot$ yielding 2.7 close encounters.

Gravitational focussing increases these encounter rates at the massive end of the distribution, the ratio of gravitational to geometric target areas being

$$r = 1 + (\frac{V_e}{V})^2 \qquad (9)$$

where V_e represents the escape velocity from the surface of the GMC of radius R, and we take V = 20 kms^{-1}. Thus for a GMC of mass 10^6 $M_\odot$ and radius 20 pc, V_e = 31 km s^{-1} and r = 3.2. For radius 40 pc, V_e = 22 kms^{-1} and r = 2.2. The number of close encounters with massive GMCs (say $> 5 \times 10^5\ M_\odot$) is therefore at least doubled to $\sim$5. A 'best estimate' for the number of close encounters with GMCs of mass $> 10^5\ M_\odot$ then becomes $\sim$10, half of which are with GMCs of mass $\gtrsim 5 \times 10^5 M_\odot$. It seems unlikely that the encounter rate would be less than half of this, on present assumptions.

Bailey (1983) has pointed out that encounter rates are lowered by a factor $\sim$1.5-2 when a simple slab model for the vertical distribution of GMCs is replaced by an exponential one; on the other hand stellar kinematic evidence shows that the Galaxy has been 'rougher' in the past, by a factor up to $\sim$10 (Lacey 1984), whence the mean number density of GMCs over the history of the Solar System has probably been about double the current value. I shall assume that these factors cancel out.

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Consider first only encounters with $p > p_1 = 20$ pc, out to a large distance p_2 pc, and assume that these are all flyby. Each passage produces a velocity change of a comet relative to the Sun given, on the impulse approximation, by

$$\delta V = \frac{2Gm}{pV} \quad \frac{d}{p} \tag{10}$$

G the gravitational constant and d the Sun-comet projected distance. In time t the Solar System interacts with $n(m)dm \times Vt \times 2\pi (1+[\frac{2G}{pV^2}]m)$ pdp nebulae in the range (m,m+dm) and (p,p+dp), where the enhancement of rate due to gravitational focussing has been allowed for. Assuming the velocity increments add randomly, the r.m.s. velocity σ_c induced in comets by passages >20pc is given by

$$\sigma_c^2 = 2\pi \; Vt \int_{p_1}^{p_2} \int_{m_1}^{m_2} \left(\frac{2Gm}{pV} \quad \frac{d}{p}\right)^2 \left(1 + [\frac{2G}{pV^2}] \; m\right) n(m)dp \; dm \tag{11}$$

or, with (1),

$$\sigma_c^2 = \sigma_{nf}^2 + \sigma_f^2 \tag{12}$$

where

$$\sigma_{nf}^2 = 4\pi \frac{G^2 \; t}{V} \left(\frac{d}{p_1}\right)^2 \left(\frac{2-\alpha}{3-\alpha}\right) m_2 \rho \tag{13}$$

and

$$\sigma_f^2 = \frac{16\pi}{3} \; \frac{G^3 \; t}{V^3} \; \left(\frac{d}{p_1}\right)^2 \; \left(\frac{2-\alpha}{4-\alpha}\right) \; \frac{m_2^{\;2}\rho}{p_1} \tag{14}$$

(σ_{nf},σ_f) representing the dispersion components due to the non-focussing and focussing components respectively of (11). Their ratio is

$$\frac{\sigma_f}{\sigma_{nf}} = \left[\frac{4}{3} \; \frac{G}{V^2} \left(\frac{3-\alpha}{4-\alpha}\right) \quad \frac{m_2}{p_1} \right]^{1/2} \tag{15}$$

which, for $V = 20$ km s^{-1}, $\alpha = 1.5$, $m_2 = 3 \times 10^6 \; M_\odot$, $p_1 = 20$ pc, is 1.15, yielding $\sigma_c = 1.53 \; \sigma_{nf}$.

Assuming d = 20,000 a.u. and t = 4.5 Byr in (13), one finds

$$\sigma_{nf}^2 = 4.8 \times 10^{-6} \;\; m_2\rho \;\; (\text{cm s}^{-1})^2$$

which, with $m_2 = 3 \times 10^6 \; M_\odot$ and $\rho = 5 \times 10^7 \; M_\odot \; \text{kpc}^{-3}$ as before, gives

$$\sigma_{nf} = 0.27 \; \text{kms}^{-1}$$

and

$$\sigma_c = 0.41 \; \text{kms}^{-1}$$

It is clear from (13) that the bulk of the power input to the Oort cloud comes from the closest encounters. Within 20 pc, we may assume that the most significant close encounters will involve actual passage of the Solar System through a GMC. It may be shown (CN 1983, Bailey 1983) that the cumulative effect of penetrating encounters contributes 1.6 times as much energy as the non-focussing component of flyby encounters. Thus the velocity dispersion induced by the penetrating encounters is roughly $\sigma_p = 0.27\sqrt{1.6} = 0.34$ kms^{-1} and the overall effect of the molecular clouds is to introduce a dispersion

$$\sigma = (\sigma_p^2 + \sigma_c^2)^{1/2}$$

or

$$\sigma = 0.53 \text{ km s}^{-1}$$

If the r.m.s. velocity induced by stars ($\sim$0.14 km s^{-1}) is added, this increases to $\sim$0.55 km s^{-1}: stellar perturbations are a minor contributor to Oort cloud disturbance. The escape velocity at 40,000 a.u. being $\sim$0.2 km s^{-1}, the energy injected into the long-period comets is about an order of magnitude in excess of that required to disperse it even assuming it has no initial kinetic energy.

Two important considerations have been omitted from the analysis. First, the energy input is a random walk, but with an outward drift: there is a systematic unbinding imposed on the random energy changes. This systematic component is comparable to the random one already discussed (CN 1982a). Second, real GMCs are not homogeneous spheres but are highly structured objects comprising many clouds within them; a typical filling factor is $\sim$0.05. It is readily shown, by application of these formulae suitably modified, that for reasonable mass distributions of internal structure subject to the filling factor = 0.05 constraint,the effect of clumpy internal structure is generally larger than that of the GMC as a whole. And probably substantially larger: e.g. in the molecular cloud complex towards M17 about a third of the mass is in four fragments with radii 3-6 pc (Elmegreen & Lada 1976); but a high resolution study of one fragment (M17SW) of mass 20,000 $M_\odot$ reveals it to comprise substructure of masses $\sim 50M_\odot$ and radii $\sim$16,000 a.u.: Martin et al.(1984). A single penetrating encounter with such a nebula would probably remove comets $\gtrsim 10^3$ a.u. from the Sun, and there have probably been $\sim$5-10 such encounters.

There are uncertainties, eg. the impulse approximation may be very poor for GMCs, and the past history of the solar orbit is uncertain. Nevertheless it seems very likely that the long-period comet system must be replenished from some other reservoir. The same conclusion may be reached from numerical work (e.g. Napier & Staniucha 1982), or semi-empirically from the distribution of semi-major axes of binaries (Napier & Staniucha, unpublished), or from the observed kinematic heating of stars in the disc.

THE OORT CLOUD: AN OPEN OR CLOSED SYSTEM?

The passage of the Solar System through a large GMC is likely to cause the ejection of comets orbiting more than a few 10^3 a.u. from the Sun and possibly even less. There may have been ~ 10 such penetrations. In addition the more numerous flyby encounters themselves substantially energise the Oort cloud. Evidently replenishment must be taking place, and two conceivable reservoirs are a dense, compact inner cloud or the nebulae themselves. There appear to be no prima facie astrophysical objections to the occurrence of comets in either source. The question of provenance then reduces to that of mass and depletion timescale, which in turn depends on the celestial mechanics of unbinding or capture.

It now seems from the ~ 30 Myr periodicity in the cratering record (Seyfert & Sirkin 1979; Rampino & Stothers 1984; Alvarez & Muller 1984) that comets arriving from a disturbed Oort cloud are the major source of large impact cratering in the inner Solar System. (If asteroids perturbed from the main belt were the main source of large craters, it is difficult to see how such sharp, quasi-periodic impact episodes would result. Further the occurrence of such episodes was predicted on the basis of periodic comet disturbance by molecular clouds: NC 1979, CN 1982b, 1984b). However the observed lunar cratering rate shows no sign of having decayed over the past ~ 3 Byr, whence the comet reservoir must have a timescale long compared with this. The half-life of comets orbiting in the Uranus-Neptune region is ~ 1 Byr, and so a massive comet cloud in the region of these planets would appear to be ruled out. One might have a cloud just beyond this, with orbits of half-lives say $\gtrsim 5$ or 10 Byr (and therefore formed in situ), receiving just enough energisation to feed its members slowly into a zone where molecular cloud perturbations begin to take over. But in that case, because of the dominance of a few large discrete energy inputs, when a comet does begin to move outwards it is more likely to be ejected than attain zero energy, the efficiency of transfer into the long-period system being perhaps ~ 1-10%. Thus the replenishment of a cloud of $\sim 10^{11}$-10^{12} comets requires the unbinding of $\sim 10^{12}$-10^{14} which, with ~ 10 such replenishments in the history of the Solar System, implies that 10^{13}-10^{15} comets must have been thrown out altogether from the inner reservoir. To achieve this without a discernible cratering decline probably implies an inner reservoir population at least an order of magnitude greater than this, say $\sim 10^{14}$-10^{16} comets. For a mean comet mass $\gtrsim 10^{17}$ gm this implies an inner cloud mass $\gtrsim 10^{31}$-10^{33} gm, or $\gtrsim 1.7\ 10^3$ - 1.7×10^5 times the mass of the Earth! There are severe astrophysical objections to the existence of so massive an inner cloud not least of which is that the energy transferred to it by Uranus and Neptune would be substantially greater than the orbital energy of these planets. For comparison the IR emission around Vega has been interpreted by Weissman (1984) as a comet cloud of radius 85 a.u. and mass 15 $M_\oplus$ ($\sim 10^{12}$ comets).

The constancy of the cratering record, in spite of the frequency with which the Oort cloud is emptied, indicates that a very large reservoir is being tapped, and the Galaxy would appear par excellence a natural place to look for it (Clube 1978; NC 1979). The molecular cloud system may be the specific reservoir we seek, since star formation occurs in the dense cores of molecular clouds, and comet formation is likely to be an adjunct to the process. The depletion of heavy elements in the denser regions of molecular clouds is consistent with a comet number density, averaged over a GMC, of $\nu_c \sim 10^{-1\pm1.5}$ a.u.$^{-3}$ (CN 1984a; Dr Clube, these proceedings; CN and Napier & Humphries, submitted). Allowing for filling factors and density contrasts, substructures with $\nu_c > 10\text{-}10^2$ a.u.$^{-3}$ are expected to be common. The question then is, would an Oort cloud of the 'observed' population and dimensions be captured during passage through a GMC? To retain the cloud, capture would have to occur just as the Solar System was climbing out of the GMC.

Classically, the problem of capturing comets has been seen as a severe one for an interstellar cosmogony, Whipple (1975), Noerdlinger (1977), Sekanina (1976) and others finding that, to capture an Oort cloud, the Sun has to be co-moving ($\lesssim 2$ kms^{-1}) with a comet cloud of very small velocity dispersion ($\lesssim 1$ kms^{-1}). However in such studies the ambient potential was taken to be static, the Sun capturing only those comets which crossed a fixed sphere of influence (radius $\sim$40,000 a.u.) at $\lesssim 0.2$ kms^{-1}. The real situation in a GMC involves a dynamic, fluctuating potential with a solar sphere of influence which, on climbing out of a GMC potential well, may expand from $\sim 10^4$ a.u. to $\sim 10^5$ a.u. at a rate of ~ 1 kms^{-1} (the Sun moving 20 pc in 1 My, say). The problem of capture in these circumstances is discussed in CN (1984a), but a simple argument is presented here to illustrate the principles.

Neglecting factors of order unity, the number of comets entering the sphere of influence of radius r_o in a time t at less than the escape velocity v_e is given by $N_c \sim v_e t \times 4\pi r_o^2 \times f\nu_c$, where ν_c represents the number density of comets and a fraction f of them are co-moving with the Sun to within $\pm v_e$ kms^{-1}. This fraction is given approximately by $f \sim (h/\sqrt{\pi})^3 \exp(-h^2 V_\odot^2) d^3u$ with $du \sim 2v_e$ and $h^2 = 1/2\sigma^2$. Assume for example that the Sun, in climbing out of a potential well, passes at $V_\odot = 20$ kms^{-1} through a dense structure with an internal velocity dispersion such that $h^{-1} = 10$ kms^{-1}. If the chord length of passage is 2 pc, $t = 10^5$yr and $N_c \sim 3.9 \times 10^3\, r_o^2\, v_e^4\, \nu_c$. Since $v_e^4 \propto r_o^{-2}$ the radius of the sphere of influence cancels out and hence N_c is not sensitive to the detailed geometry and masses involved. One finds $N_c \sim 2.3 \times 10^7\, \nu_c$ resulting in the capture of $\sim 10^9$ comets if $\nu_c \sim 10^2$ a.u.$^{-3}$. However, one expects that, since the velocities of bodies leaving the GMC decline relative to it, they will, statistically, also decline relative to each other. In particular, the sphere of influence is a purely formal concept and the GMC potential continues to affect the motions of comets not too far inside the sphere. In essence comets entering the solar potential well at hyperbolic speed may still be trapped by the increase in the height of the well caused by the recession of the GMC. This decline in velocity dispersion may be given, approximately, by $\delta\sigma \sim \delta V_{\odot}\, r_{o}/R$ where $\delta V_{\odot}$ represents the decline in the velocity of the Sun as it climbs out of the potential well of a structure of scale length R. It is easily found that the 'capture window' $\pm v_e$ may be increased by a factor 2 or 3 due to this if the substructure is a few pc across and has a few $10^4 M_{\odot}$ mass, in effect increasing $N_c \propto v_e^4$ by one or two powers of ten. Accordingly, it seems that to order of magnitude an adequate capture mechanism may exist: the Sun merely has to pass through a moderately dense substructure as it leaves a GMC.

CONCLUSIONS

1. There may have been ~10 actual penetrations of GMCs during the course of Solar System history.

2. Within the acceptable ranges of molecular cloud parameters it is to be expected that the Oort cloud has been removed beyond a few 10^3a.u. perhaps ~10 times in the past 4.5 Byr. Stars are a relatively minor contributor to perturbations of the Oort cloud.

3. Replenishment by unbinding from a very dense inner cloud has yet to be modelled quantitatively, taking full account of GMC perturbations, but a qualitative discussion is given which suggests that the hypothesis may not work.

4. On the other hand, capture from GMCs with a reasonable comet number density may take place and is consistent with the steady cratering rate.

5. The dynamical picture described here forms the basis for a theory of terrestrial catastrophism first described in NC(1979) and developed in CN 1982b, 1984b (and see Dr. Clube's contribution to these proceedings). Amongst the predictable (and predicted) consequences of the theory are mass extinctions of species and geophysically disturbed epochs. These are caused by episodes of bombardment which recur with galactic periodicities and are dominated by the disintegration products of the very largest comets.

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DISCUSSION

J.A. Fernandez: In my opinion our current knowledge of GMCs is too poor to make strong statements on the capture-disruption of cometary clouds. We still do not know very well the general properties of GMCs such as their size, mass and frequency of encounters with the solar system, let alone the problem of discussing their fine structure. I think that changes in the values of the parameters within the currently accepted ranges will lead to quite different conclusions regarding the disruption of cometary clouds and the capture of new ones by the solar system.

W.M. Napier: Dr Fernandez's opinion should be demonstrated using recently published work on GMCs. In any case the analysis is based not just on the measured molecular cloud properties but also on a comparison with the observed heating of the stellar disc: the conclusion, that the energy injected into the long-period comet system over 4.5 Byr is one or two powers of ten greater than its binding energy, can be reached without reference to GMCs. Further evidence on the dynamics and origin of the Oort cloud should be forthcoming from the cratering record and the geochemistry of iridium - enhanced layers of probably cometary origin (cf the talk by Dr Clube, this volume).

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