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UPPER LIMITS TO THE MASSES OF OBJECTS IN THE SOLAR COMET CLOUD

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ABSTRACT

The lack of a large steady stream of long-period comets with semimajor axes less than 2×10^4 AU rules out the Sun having a companion more massive than about 0.01 $M_\odot$ with a semimajor axis less than about 1×10^4 AU. Any companion with a semimajor axis between 1×10^4 AU and 5×10^4 AU has more than a 50% probability of having entered the planetary system during the lifetime of the Solar System. The lack of apparent damage to the planetary system rules out any companion more massive than about 0.02 $M_\odot$ with a semimajor axis less than about 5×10^4 AU.

INTRODUCTION

Recent discussions of the hypothetical solar companion Nemesis have renewed interest in the possibility that the sun may have other distant companions of planetary or stellar mass. In addition, work by Shoemaker and Wolfe (1982) suggests that the mass spectrum of comets may be similar to that of the asteroids, so most of their mass is tied up in a relatively few massive comets. Finally, the work of Hills (1982) and Hills and Sandford (1983 a,b) indicates that very massive comets could form in the outer collapsing parts of the protosun by the driving together of the dust clumps by the radiation pressure from the sun and neighboring protostars.

In this paper we use various dynamical constraints to determine the maximum mass of solar companions within the solar comet cloud. These constraints include the observed lack of long-period comets with semimajor axes less than about 2×10^4 A.U. and the observed lack of damage to the planetary system which would be produced by such a solar companion if it were perturbed by passing stars into an orbit that brought it into the planetary system.

We shall not consider possible future constraints on massive objects from visual observations and infrared surveys such as the the recently completed IRAS survey. Visual surveys are most useful in finding a distant nuclear-burning companion such as the hypothetical companion Nemesis if it has a mass exceeding the Kumar limit of 0.07 $M_\odot$. A Planet X a short distance beyond the known planetary system might also be detected optically from reflected sunlight. An infrared survey such as that done by IRAS could be effective in searching for a companion more massive than Jupiter but less massive than the Kumar limit. Such a brown dwarf would have a surface temperature of a few hundred degrees Kelvin and could be quite conspicuous at far infrared wavelengths. Davidson (1975) gave an early discussion of the possiblity of detecting a solar companion in the optical and infrared.

DYNAMICAL CONSTRAINTS ON THE MASSES OF SOLAR COMPANIONS

From the Semimajor Axis of Inner Edge of the Oort Comet Halo

The observed absence of long period comets with semimajor axes less than about 2×10^4 A.U., which was first noted empirically by Oort (1950), places severe constraints on the mass of any companion with a semimajor axes less than about 2×10^4 A.U.

The fact that long period comets are confined to the Oort Halo in which the semimajor major axes exceed 2×10^4 A.U. is the result of the interplay between perturbations due to Jupiter and Saturn which tend to eject all comets which cross their orbits into hyperbolic orbits and the perturbations due to passing stars which tend to deflect some comets not in planet-crossing orbits into such orbits (Hills 1981). For comets in relatively short period orbits of small semimajor axes, the planetary perturbation dominate so few of these objects enter within the orbits of Jupiter and Saturn at perihelion. For comet orbits of sufficiently long period and large semimajor axis, the perturbations by passing stars dominate, so the fraction of the comets in such distant orbits which cross within the orbits of Jupiter and Saturn at perihelion is determined purely by statistical equilibrium and is independent of the efficiency at which the planets eject such comets into hyperbolic orbits. The theoretical crossing point between these two perturbations regimes is just at the observed inner edge of the Oort Halo or at a semimajor axis of about 2×10^4 A.U. (Hills 1981). In the absence of a massive solar companion, the inner edge of the Oort comet halo would usually be near its present distance even if the complete solar comet cloud extends smoothly from the outer part of the planetary system to the outer edge of the Oort Halo. Occasionally, there would be intense, but brief comet showers generated when comets with semimajor axes less than 2×10^4 A.U. are deflected into the planetary system by infrequent, unusually close stellar encounters.

If the sun had a sufficiently massive companion in an orbit lying inside the observed Oort halo then pertubations by the companion would deflect a constant stream of comets with semimajor axes less than 2×10^4 A.U. into the planetary system. Hills (1984) found that the minimum mass of Nemesis needed to produce comet showers is 0.01 $M_\odot$. This minimum mass is also applicable to a solar companion having a smaller semimajor axis than Nemesis. The lack of a constant stream of comets with semimajor axes less than 2×10^4 A.U. rules out any companion more massive than 0.01 $M_\odot$ in a circular orbit with a semimajor axis less than 2×10^4 A.U. If the orbit of the companion is highly eccentric, it would spend most of its time at aphelion. Even in this case, we may rule out any companion more massive than 0.01 $M_\odot$ in an orbit with a semimajor axis less than 1×10^4 A.U.

These arguments also place constraints on massive companions in highly eccentric orbits with semimajor axes greater than 2.0×10^4 A.U. The solar companion Nemesis would be in this category. Such a companion would produce periodic comet showers if it passes within the 2.0×10^4 A.U. limit at perihelion. The absence of any periodicities other than the 26 Myr period found (maybe) in the fossil record appears to rule out any distant companion other than Nemesis in an orbit which brings it within 2.0×10^4 A.U. at perihelion. Of course, this criterion says nothing about a companion in a very distant orbit with a perihion distance greater than 2×10^4 A.U. The loss cone of comets in the Oort halo are always filled by the perturbations due to passing stars so the additional perturbations due to such a distant companion could make no further contribution to the number of Oort-halo comets in planet-crossing orbits.

From the Lack of Damage to the Planetary System

The lack of damage to the planetary system also places constraints on the masses of solar companions, although, unlike the constraints imposed by the observed inner edge of the Oort halo, the results are statistical rather than deterministic since the lack of damage depends not only on the mass of the companion but also on the probability that it was perturbed into an orbit which brought it into the planetary system.

The computer simulations given in Hills (1985a) indicate that no solar companion more massive than 0.02 $M_\odot$ has entered the planetary system. The passage of such an object through the planetary system would have left the planets in more highly eccentric orbits than observed. The planetary orbits would also be less coplanar than now observed.

If the semimajor axis of the orbit of the companion is less than 500 A.U. then stellar encounters are infrequent enough that its orbit has remained virtually unchanged since the formation of the solar system (Hills 1984). The only constraint on such a companion from a lack of damage to the planetary system is that its initial (and present) perihelion distance be well beyond the orbit of Pluto. From the data in Hills (1984), I estimate that its perihelion distance has to be at least twice the semimajor axis of Pluto if its mass is 0.02 $M_\odot$, and it is larger if it is more massive. However, it would still produce comet showers which are not observed.

For a companion with a semimajor axes between 500 A.U. and 2×10^4 A.U. the probability of its having entered the planetary system depends on the frequency of stellar encounters. Using a loss-cone analysis which was first applied to the problem of finding the rate at which black holes swallow stars in galactic nuclei, I find that the probability that a companion of semimajor axis a has crossed within distance q of the sun to be given by

$$P_N=1-\left(1-\frac{2q}{a}\right)^N \qquad (1)$$

where

$$N=1626\left(\frac{a}{2\times10^4\ \text{A.U.}}\right)^2 \qquad (2)$$

is the number of independent loss cone fillings (Hills 1985b)

For semimajor axes greater than 2×10^4 A.U. the probability of the companion having crossed within distance q of the sun is purely a function of its semimajor axis. The stellar perturbations are frequent enough that the loss cone is always filled. The number of independent loss cone fillings is just the number of orbital revolutions made by the companion. The size of the loss cone, which determines the probability that the companion enters the planetary system in each orbital period, is just determined by the orbital semimajor axis of the companion. The probability that the companion has entered the planetary system in 4.6 Gyrs is given by Equation (1) with

$$N = \frac{t}{p} = 1626 \left(\frac{2\times10^4 \text{ A.U.}}{a}\right)^{3/2} \qquad (3)$$

now being the number of orbital revolutions of the companion since the formation of the solar system.

We find that the probability P_N that the companion has entered within the orbit of Saturn, which requires a perihelion distance less than q=10 A.U., drops from $P_N=0.80$ at $a=2\times10^4$ A.U. to $P_N=0.50$ at $a=2.8\times10^4$ A.U. to $P_N=0.03$ at $a=1\times10^5$ A.U. The probability that it has crossed the orbit of Uranus, which requires that q=30 A.U., falls to $P_N=50\%$ at $a=4.35\times10^4$ A.U. For Pluto with q=40 A.U. this becomes $P_N=50\%$ at $a=5\times10^4$ A.U.

We conclude from the lack of damage to the planetary system that there is less than a 50% chance of the sun having a companion more massive than 0.02 $M_\odot$ with a semimajor axis less than about 5×10^4 A.U.

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