A SEARCH FOR STARS PASSING CLOSE TO THE SUN

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ABSTRACT

We have combined Hipparcos proper motion and parallax data for nearby stars with ground-based radial velocity measurements to find stars which may have passed (or will pass) close enough to the Sun to perturb the Oort cloud. Close stellar encounters could deflect large numbers of comets into the inner solar system, with possibly serious consequences for the impact hazard on the Earth. Only one star (Gliese 710) is found with a predicted closest approach of less than 0.5 parsec, although several stars come within about 1 parsec during a ±8.5 Myr interval. In most cases the uncertainty in closest approach distance is dominated either by uncertainties in published radial velocity measurements or by uncertainties in the barycentric motion of binary systems. We have begun a program to obtain new radial velocities for stars in our sample with no previously published values.

Key words: Space astrometry; Comets: general; Stars: distances; Stars: kinematics.

1. INTRODUCTION

The solar system is surrounded by a vast cloud of about $10^{12} - 10^{13}$ comets with orbits extending to interstellar distances, called the Oort cloud, with a total estimated mass of some tens of Earth masses (Oort 1950, Weissman 1990). These cometary orbits are perturbed by random passing stars, by giant molecular clouds and by the galactic gravitational field. In particular, close or even penetrating passages of stars through the Oort cloud can deflect large numbers of comets into the inner planetary region (Hills 1981), initiating Earth-crossing cometary showers and possible collisions with the Earth. Such impacts could cause biological extinction events. Some terrestial impact craters and stratigraphic records of impact and extinction events suggest that such showers may have occurred in the past. Dynamical models (e.g. Hut et al. 1987) show that a cometary shower has a typical decay time of about $2 - 3$ million years.

Evidence of the dynamical influence of close recent stellar passages on the Oort cloud could come from the observed distribution of cometary aphelion directions. Although the distribution of long-period (10^6 to 10^7 years) comet aphelia is largely isotropic on the sky, some non-random clusters of orbits exist and it has been suggested that these groupings record the tracks of recent stellar passages close to the solar system (Biermann et al. 1983). However, Weissman (1993) showed that it would be difficult to detect a cometary shower in the orbital element distributions of the comets, except for the inverse semi-major axis, $1/a_o$, energy distribution, and that there is currently no evidence of a cometary shower in this distribution.

Some work has been done in the past to search for stellar perturbers of the cometary cloud. Mülläri & Orlov (1996) studied close encounters with the Sun by 1946 stars contained in the Preliminary Version of the Third Catalogue of Nearby Stars (Gliese & Jahreiss 1991). They found that 3 stars may have had and 22 can have encounters with the Sun within 2 parsecs, with predictions being valid over about ± 1 million years from the present epoch. Matthews (1994) made a similar study although it was limited to stars from the solar neighbourhood within a radius of about 5 pc, and he lists close approach distances for 6 stars in the near future (within $5{\times}10^4$ yr from now).

Nevertheless, the accuracy of most ground-based parallax and proper motion measurements is typically limited to several mas or mas per year, respectively. This measurement accuracy imposes a severe limitation on the accuracy of predictions of past or future close stellar passages.

Our aim is to search for nearby stars which have passed or will pass sufficiently close to the Sun to cause a significant perturbation of the orbits of comets in the Oort cloud. In order to determine these close approaches as precisely as possible we have used the very accurate astrometric data (mean precision of 1 mas and 1 mas per year for the parallax and proper motion, respectively) from the Hipparcos satellite.

2. OBSERVATIONAL DATA AND ANALYSIS

Significant perturbations of the Oort cloud are possible out to a distance of about $2-3$ pc. We selected 1208 stars from the Hipparcos Catalogue (ESA 1997), whose proper motion combined with an assumed radial velocity of 100 km s^{-1} implied an impact parameter of 3 parsecs or less. This radial velocity is five times the local stellar velocity dispersion, to allow intrinsically higher velocity stars to be included. Thus, stars whose proper motion in mas per year were less than 0.06 times the square of the parallax in mas, for parallax values greater than 4.5 mas, are the best candidates to have approaches within 3 pc from the Sun over $\pm$10 Myr from the present epoch. For smaller parallax values the implied proper motion limit is at or below the Hipparcos measurement accuracy.

In order to determine past or future close encounters with the Sun, we searched for published radial velocity measurements in the literature. We found values for 472 of our 1208 stars (about 40 per cent of the sample) which were combined with the Hipparcos satellite data to calculate the time and distance of the close passages assuming straight line motion. 156 out of the 472 stars are recognized members of binary or multiple systems.

For some of these binary or multiple systems the systemic radial velocity is reported, whereas for some other systems it is not clear whether it is the systemic radial velocity or the radial velocity of one component. Other stars show long-term changes in their radial velocities that could imply that they belong to long-period multiple systems. In some papers the radial velocity uncertainty is not given, or the authors only report the probable error for the list of observed stars in which the one of interest is included. In these cases it is difficult to derive an accurate error estimate for the calculated closest approach distance and epoch.

We have investigated several effects which might make the simple linear motion model used above inadequate, including multiple scattering by other stars along a star's path toward or away from the Sun, galactic rotation, and oscillation perpendicular to the plane of the Galaxy. The effect of stellar interactions is small, about 4.5 arcsec deflection for a solar mass star passing 1 parsec from another solar mass star with a relative velocity of 20 km s^{-1}. Even over a path length of 100 parsec, the rms deflection due to such encounters (assuming a stellar density of 0.1 pc^{-3}) is less than 1 arcminute. This deflection at 100 parsec would change the impact parameter by less than 0.03 parsec. The effect of galactic rotation is also unimportant out to a distance of at least 100 pc, since it is only the time derivative of the rotation-induced proper motions which is important. Oscillation about the plane of the Galaxy can cause differential acceleration between a star and the Sun, but over the times and distances typically considered here this also results in only a small change in impact parameter.

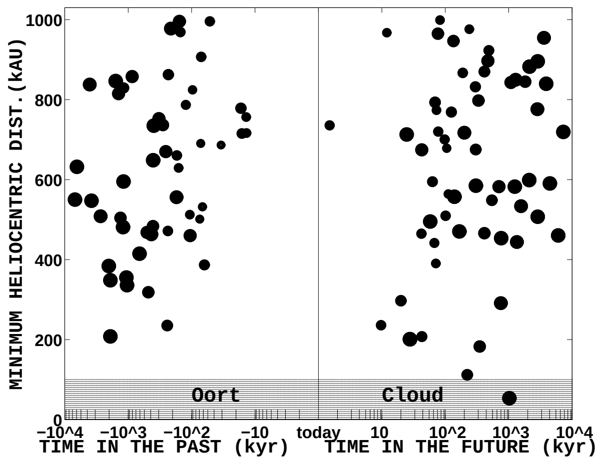

Figure 1. Closest approach distance (10^3 AU) versus time (10^3 years). The outer radius of the Oort cloud is approximately 100 kAU. The visual magnitudes at the miss distance range between about -3 and about 12.

3. RESULTS

All the close stellar passages within 5 pc which we can predict are concentrated in a time interval of about $\pm$8.5 Myr. Several stars coming within about $2-3$ pc are in principle the most plausible perturbers of the Oort cloud, and particularly one of these, GL 710 (HIP 89825), may have a future penetrating passage through the outer Oort cloud.

The predicted closest approach distances versus time of past (negative times) or future (positive times) encounters are shown in Figure 1. The size of the circle is proportional to the visual magnitude of the star at the miss distance. From this plot we see that the passages at large times are dominated by the brighter stars. This suggests an observational bias due to the fact that most of the stars that had or will have a close passage at large times can only be currently observed if they are intrinsically bright. Uncertainties in time and distance of the closest passages have mean values of about 20 per cent and 30 per cent, respectively. About 50 per cent of the sample have errors above 10 per cent, whereas about 15 per cent of the sample have errors over 50 per cent.

The average number of stars passing within any distance, D, of the Sun is given by N = π D^2 v ρ_*, where v is the velocity of the Sun relative to the local stars and ρ_* is the local density of stars (Weissman 1980). Assuming that v = 20 km s^{-1} and $\rho_* = 0.08$ pc^{-3} (Allen 1973) one finds N = 5.1 D^2 Myr^{-1}, where D is measured in pc. Assuming v = 35 km s^{-1}, then N = 9 D^2 Myr^{-1}. A logarithmic plot of the cumulative number of predicted encounters from our Hipparcos data, between the Sun and passing stars within 5 pc during a time interval of $\pm$1 Myr for stars with measured radial velocities (40 per cent of the total sample), is shown in Figure 2.

The dashed line in the figure is a rough fit to the data assuming a slope of 2.0. Assuming similar statistics for the total sample, we find a value of 5 stars per Myr

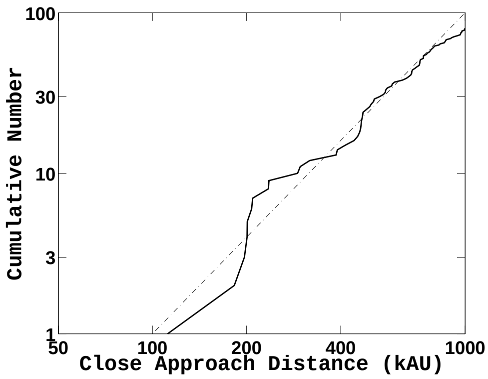

Figure 2. Cumulative number of predicted stellar encounters versus closest approach distance within ±1 Myr.

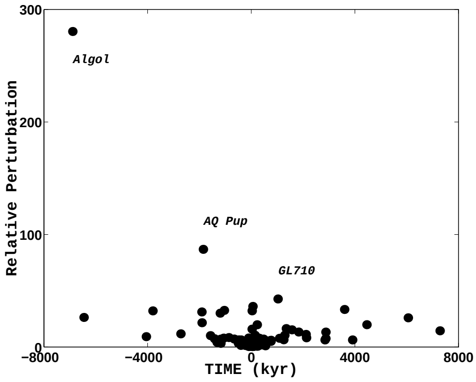

Figure 3. Relative perturbing effect of predicted stellar encounters.

passing within 1 pc, in good agreement with the prediction. A least-squares fit to the data finds a slope of 1.88. The lower slope to the fitted data is probably indicative of observational incompleteness. The Hipparcos data are complete down to about magnitude 9 and consequently, fainter low mass stars near the periphery of our search area were likely missed. This observational incompleteness is also evident in the decrease in encounter frequency and the increase in the mean brightness of the stars encountering the solar system as one moves away from the present epoch in time.

3.1. Radial Velocities

In most cases the uncertainty in the closest approach distance is dominated either by uncertainties in the published radial velocity measurements or by uncertainties in the barycentric motion of binary systems. For the stars in our sample that are part of multiple stellar systems, orbital motions could contribute to the measured values of proper motion and radial velocity, and our estimates of the uncertainty in miss distances may have to be increased. Some single stars are found to have long-term changes in their measured radial velocities, which could be interpreted either as evidence for long-period binary systems with unidentified companions or as the result of fitting different spectral lines at different epochs.

3.2. Past and Future Close Approaches

A total of 113 stars are predicted to come within a distance of 5 pc during a time interval of about ±8.5 Myr, with roughly equal numbers of close approaches in the past and future. The dynamical effect of these stars on the Oort cloud depends not only on their proximity but also on their mass and how long the encounter lasts. The relative influence of these stars on the cometary orbits can be estimated from the differential attraction exerted on the Sun and a comet in the cloud, which results in a net change of the velocity of the comet with respect to the Sun. The net velocity perturbation, ΔV, on an Oort cloud comet due to a single close stellar passage can be shown to be approximately proportional to $M_* V_*^{-1} D^{-1}$, where M_* is the mass of the star, V_* its total velocity relative to the Sun and D the miss distance (Oort 1950).

The relative magnitude of the stellar perturbation on the Oort cloud as a function of time is shown in Figure 3. The magnitude is given in arbitrary units and represents a first-order measure of the gravitational influence of one close stellar passage relative to the others. This identifies the stars most likely to perturb the Oort cloud, although the real perturbation on the cometary orbits can only be estimated through dynamical simulations.

The most significant perturber in our data set is Algol (HIP 14576), a triple star system, whose close encounter with the Sun, 7.3 Myr ago at 3 parsecs, was determined by VLBI astrometry by Lestrade et al. (1997), in good agreement with the values of 6.8 Myr and 2.7 pc from the present work within the uncertainties. The relative perturbation has been calculated considering the total mass (about 6 $M_\odot$) of the three stars. Both the total mass and the slow passage seem to combine efficiently to compensate for the comparatively large miss distance. The second potentially major perturber is the massive star AQ Pup (HIP 38965), with a miss distance of 1.7 pc. Both Algol and AQ Pup had their close passages in the past. GL 710 is the most significant perturber in the future.

In addition, the cumulative effect of close passages of several random stars not necessarily belonging to the same multiple system may also play an important role. Stochastic encounters with several massive stars closely spaced in time might cause a significantly larger effect than considering them separately. Such groups of encounters are present in the past at about 2 Myr and about 1 Myr, and one in the future within the next 0.1 Myr. Note, however, that some of the closest approach times have large uncertainties.

3.3. The Future Close Passage of GL 710

GL 710 is a late-type dwarf star (dM1 according to Joy & Abt 1974; K7 V according to Upgren et al.

1972) with a mass of about 0.4 − 0.6 $M_\odot$ located at a present distance of 19.3 pc from the Sun and characterized by having a proper motion much smaller than its parallax. Residuals in proper motion measurements suggested a possible periodicity of 1700 days (Osvalds 1957). A slight indication of a period of this order was also found by Grossenbacher et al. (1968), although they considered this as not of great significance. One speckle measurement on the possible binary nature of this star did not detect any companion with $\Delta m \sim 3$ and angular separation in the range 0.05 − 1 arcsec (Blazit et al. 1987). Furthermore, the Hipparcos astrometric data do not show any evidence of the periodicity of 1700 days for an observation period of 3.4 years (Kovalevsky 1996).

Nevertheless, GL 710 does appear to exhibit long-term radial velocity changes, and from the radial velocity values reported we suspect that GL 710 may be a long-period binary star. Measurements made in the 1940's show radial velocities more negative than -20 km s^{-1}, whereas observations between 1984 and 1997 report values less negative than -15 km s^{-1} (with one exception of -26.3 ± 15.0 km s^{-1} which can be ruled out due to its large uncertainty). Unfortunately, a gap in the observations for forty years between old and more recent measurements prevent us from knowing if the radial velocity changed smoothly during this time. Any unpublished previous proper motion, parallax and radial velocity measurements would help us better understand the long-term motion of GL 710.

Some assumptions are thus required in order to obtain an estimate of the closest approach distance for this star. First, as mentioned above, one possible interpretation is to consider GL 710 as part of a long-period binary. Assuming a circular orbit and taking radial velocities of -23.3 km s^{-1} and -13.9 km s^{-1} (the radial velocity with the lowest uncertainty of the more recent measurements) as upper and lower limit, respectively, we obtain a radial velocity of the binary system of -18.6 km s^{-1}. With these assumptions, GL 710 could have a future close encounter with the Solar System in about 1 Myr, passing through the Oort cloud at an estimated closest distance of 5.3 $\times 10^4$ AU from the Sun. However, orbital contributions to the measured proper motion could increase the uncertainty of the miss distance.

On the other hand, a different interpretation could be adopted. We could assume that the radial velocity values in the 1940's resulted from fits to spectral lines different than the ones fitted in more recent measurements and also that the latter are the most reliable measurements, yielding a value of -13.9 km s^{-1}. In that case, we obtain a future closest approach distance of 7.0 $\times 10^4$ AU in about 1.3 Myr.

If it is indeed a binary system, the measured radial velocity of GL 710 will continue to slowly change and will be constant if not. We should be able to distinguish between these possibilities in less than a decade with ± 1 km s^{-1} measurements.

4. CONCLUSIONS

In order to complete our study, we are currently carrying out an observational program to measure radial velocities for the stars in our initial Hipparcos sample of 1208 stars with no previously published values. This will allow us to estimate miss distances for a larger fraction of stars and to identify possible multiple star systems. Those future measurements, together with the access to the total sample of the Hipparcos Catalogue (ESA 1997), will likely increase the number of stars with predicted close passages. The present work is a starting point for further dynamical studies of the influence of these close stellar passages on the Oort cloud.

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