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PRELIMINARY STUDY ON STELLAR PERTURBATIONS OF THE OORT COMET CLOUD

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Abstract. We simulate the injection of comets from the Oort Cloud into the observable region due to stellar passages. These are sorted according to parameters measuring the strength of the average impulse received by the comets and compared with regard to the number of resulting injections. We demonstrate that massive stars play a major role in spite of their low encounter frequency, and that in combination with the Galactic tide each stellar passage has a long-term effect on the injection rate.

1. INTRODUCTION

Since the famous paper by Oort (1950) long period comets are assumed to originate in a huge spherical reservoir (the *Oort Cloud*), located between a few thousand and a hundred thousand astronomical units. The orbits of these comets may be perturbed by the Galactic tidal field and stars passing close to the Sun. Rickman et al. (2008) showed that these two perturbers, when acting simultaneously, generate a strong synergy that significantly increases the flux of comets toward the observable region (defined by $r < 5$ AU, r being the heliocentric distance). Our scope is now to investigate the influence of single stellar encounters on this flux.

2. STAR SAMPLES AND INITIAL CONDITIONS

We constructed 65 sequences of stellar encounters as follows. Each sequence includes 20 encounters occuring at intervals of 250 Myr during a 5 Gyr total time span, the first encounter occurring 125 Myr after the beginning of the simulation. Each sequence uses only one spectral type. As in Rickman et al. (2008), 13 spectral types are considered: 11 main sequence types (B0, A0, A5, F0, F5, G0, G5, K0, K5, M0, and M5) plus red giants and white dwarfs. Their masses and velocities are found in the same way as in Rickman et al. (2008). Five different sequences are calculated for each spectral type. The impact parameter $d_\odot$ with respect to the Sun is randomly chosen between 3×10^3 AU and 4×10^5 AU with a uniform distribution in $\log d_\odot$.

These 65 stellar encounter sequences perturb a cloud of 10^6 fictitious comets with the following initial orbital elements: the semi-major axes a are randomly chosen such that 3000 AU $< a <$ 50 000 AU with an uniform distribution in a^{-1}, and the eccentricities obey $0 < e < 1$ with a distribution proportional to e such that $q = a(1-e) > 32$ AU. The mean anomaly M and the Galactic orienting angles (inclination i, argument of perihelion ω, longitude of the ascending node Ω) are chosen randomly according to an uniform distribution between 0 and 2π. Each comet is integrated until $r < 15$ AU or $r > 4 \times 10^5$ AU for a maximum time of 5 Gyr.

3. DIRECT INJECTIONS

First we define "strength parameters" measuring the average impulse on the comets due to stellar encounters with different characteristics. Using the classical impulse approximation (Rickman, 1976) the impulse imparted to a comet is found from:

$$\Delta\mathbf{V} = \frac{2GM_\star}{V_\star}\left(\frac{\mathbf{b}_C}{b_C^2} - \frac{\mathbf{b}_\odot}{b_\odot^2}\right), \quad (1)$$

where $M_\star$ is the stellar mass, $V_\star$ is the stellar velocity at infinity, and $\mathbf{b}_\odot$ and $\mathbf{b}_C$ are the vectors from the Sun (resp. the comet) to the closest point on the stellar trajectory. This classical impulse is obtained considering the stellar trajectory as a straight line, with the star moving between infinite distances while the comet remains at rest.

For a close encounter with the Sun only, the impulse approximation gives:

$$\Delta\mathbf{V} \propto \frac{M_\star}{V_\star b_\odot} = I_{\text{close}}, \quad (2)$$

while in the case of a distant encounter with the Sun and the comet we obtain:

$$\Delta\mathbf{V} \propto \frac{M_\star}{V_\star b_\odot^2} = I_{\text{dist}}. \quad (3)$$

The number of comets N_S injected into the observable region during each stellar encounter is plotted versus the strength parameters I_{close} (left panel) and I_{dist} (right panel) in Fig. 1.

For each diagram, the green circles represent comets injected by encounters with low-mass stars (G0 to M5 stars and white dwarfs), and the red circles represent those injected by encounters with high-mass stars (B0 to F5 stars and red giants) – the big circles correspond to B0 stars.

The number of comets injected by a low-mass star is well approximated by:

$$N_S \propto I_{\text{close}}^{1.56} \quad (4)$$

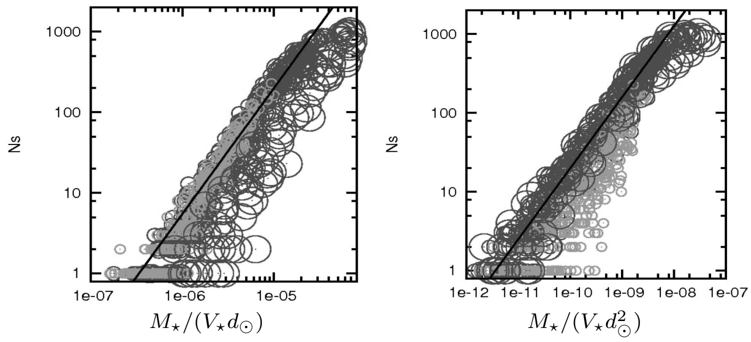

Figure 1: Number of comets entering the observable region due to a stellar encounter versus $I_{\rm close}$ (left panel) and versus $I_{\rm dist}$ (right panel). The black full lines correspond to linear fits in log scale obtained from the low-mass stars data only in the left panel and from high-mass stars only in the right panel. See text for the equations of the lines.

whereas for high-mass stars the number of comets injected is well approximated by:

$$N_S \propto I_{\rm dist}^{0.9}. \tag{5}$$

This demonstrates quantitatively that high-mass stars are long-range perturbers injecting comets from large parts of the Oort Cloud, while low-mass stars only affect comets near their tracks (the same impulse can be obtained for a passage near the comet as for one near the Sun). Due to this fact, we can expect high-mass stars to be at least as important as low-mass stars for the injection of comets from the Oort Cloud in spite of their much lower encounter frequency.

4. LONG TERM DYNAMICS

Since high-mass stars pass rarely, at first sight, their effect should be to cause temporary enhancements of the injection rate ("comet showers"), and they might have a negligible influence on the current flux of new comets. In order to check this, we performed five more simulations. Model 1 takes into account only the Galactic tide. In models 2 and 3 we suppose that the comets are perturbed by only stellar encounters involving 20 stars of type A0 and K0, respectively, as representatives of high-mass and low-mass stars. Finally, models 4 and 5 combine the influence of the Galactic tide with the stellar encounters of models 2 and 3, respectively.

Fig. 2 shows the comet injection rate into the observable region for all the models. The impact parameters with respect to the Sun are indicated for the closest encounters. Note that the direct injections (Sect. 3) are limited to the time bin of the respective encounter, as seen from the yellow peaks, but the combined models show a continuous excess with respect to the tide-only model. This shows that each stellar encounter has a long-term effect, lasting for more than 100 Myr. We interpret this as evidence that stars act not only by moving comets from outside to inside the loss cone, but they also feed comets into such phase space trajectories, where the tide

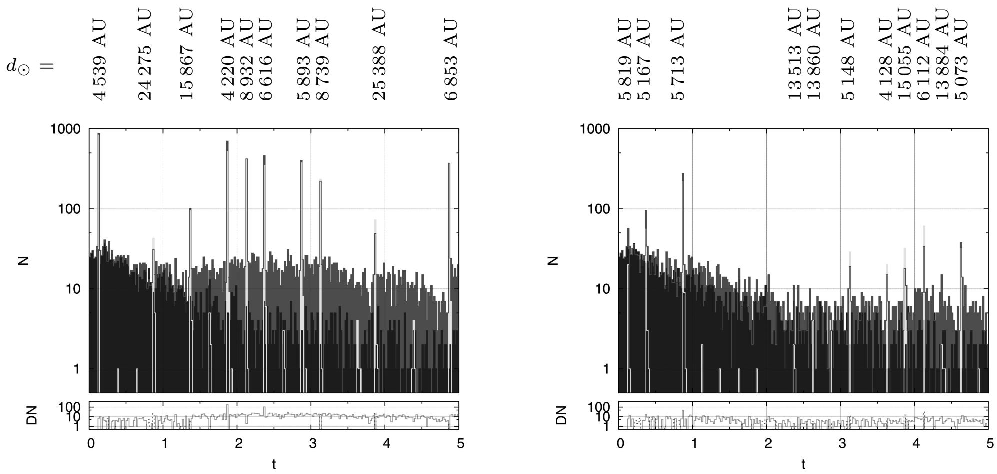

Figure 2: The upper diagrams show the number of injected comets per 20 Myr versus time (in Gyr). The blue histograms correspond to the tide-only model (N_G), the yellow to the stars-only model (N_S), and the red to the combined model (N_C). The lower graphics exhibit the values of $DN = N_S - N_G - N_S$ in each 20 Myr time bin. When positive, DN is plotted by a full green line, otherwise we use a dotted red line. The left diagrams are for A0 stars (3.2 $M_\odot$) and the right ones for K0 stars (0.78 $M_\odot$).

can eventually bring them into the observable region. Obviously, encounters with high-mass stars are much more efficient than those of low-mass stars, so even though they occur more rarely, they are likely important as drivers of the present comet flux.

5. CONCLUSION

We have started to investigate the role of stellar perturbations to inject comets from the Oort cloud into the observable region by simulating synthetic sequences of encounters with stars of given spectral types. Concerning direct injections, we find that low-mass stars act mainly via close encounters, while high-mass stars inject most comets by distant interactions. They are thus able to inject many more comets per passage and should have a large overall effect in spite of their rare occurrence. In combination with the Galactic tide we observe that a single massive star is able to fill efficiently the phase space domain from which the tide is able to send the comet into the observable region. Low-mass stars have a similar effect though much smaller. Thus the reverberations of single stellar encounters last for several hundred million years, and the present flux of new Oort Cloud comets reflects the passages of both high- and low-mass stars during a similar lapse of time in the past.

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