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Regular and Stochastic Motion of Meteoroid Streams in Halley-type Orbits

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Abstract. Despite the complicated structure of old meteoroid streams in Halley-type orbits, the positions of their ecliptic-plane crossings are insensitive to the initial conditions of ejection and have a form determined by resonances due to planetary perturbations. This allows the main observational features of meteor showers such as the η-Aquarids, Orionids, Lyrids and Perseids to be understood. A proportion of the particles ejected into such orbits librate about the centres of mean-motion resonances and produce compact streams which may lead to meteor storms.

1. Regularity and chaos in cometary orbits

Many annual meteor showers are associated with Halley-type cometary orbits with periods in the range $20 < P < 200\,\mathrm{yr}$. Such orbits frequently show mean-motion commensurabilities with Jupiter of the form $1{:}j$, and this leads to the formation of characteristic structures in the corresponding meteoroid stream. If the orbit is of longer period, with a reciprocal semi-major axis $w < 0.03\,\mathrm{AU}^{-1}$, all the centres of resonances are usually unstable (Emel'yanenko 1992a), and in this case the phase-space evolution of the meteoroid stream is similar to that of a diffusion process (Zaslavsky & Chirikov 1971, Chirikov 1979, Lichtenberg & Liberman 1983). The variance $\sigma^2(w)$ after the particles have performed an average of $\overline{N}$ revolutions may then be written (Emel'yanenko 1992a) $\sigma^2(w) = \overline{N}\sigma_P^2(w) + \sigma_0^2(w)$, where σ_P is the standard deviation in $1/a$ per revolution produced by planetary perturbations and σ_0 is the corresponding spread for the ejected particles. This shows that the initial conditions become unimportant after a sufficient time and the dynamical evolution, which is chaotic, is dominated by planetary perturbations.

In the case of Halley-type orbits, however, the centres of resonances can be relatively stable for long periods of time; their parameters have been determined for the main meteoroid streams by Emel'yanenko (1988). Librations about the centres of these resonances may persist for hundreds of revolutions (Marsden 1970, Emel'yanenko 1985, Carusi & Valsecchi 1987, Chambers 1995).

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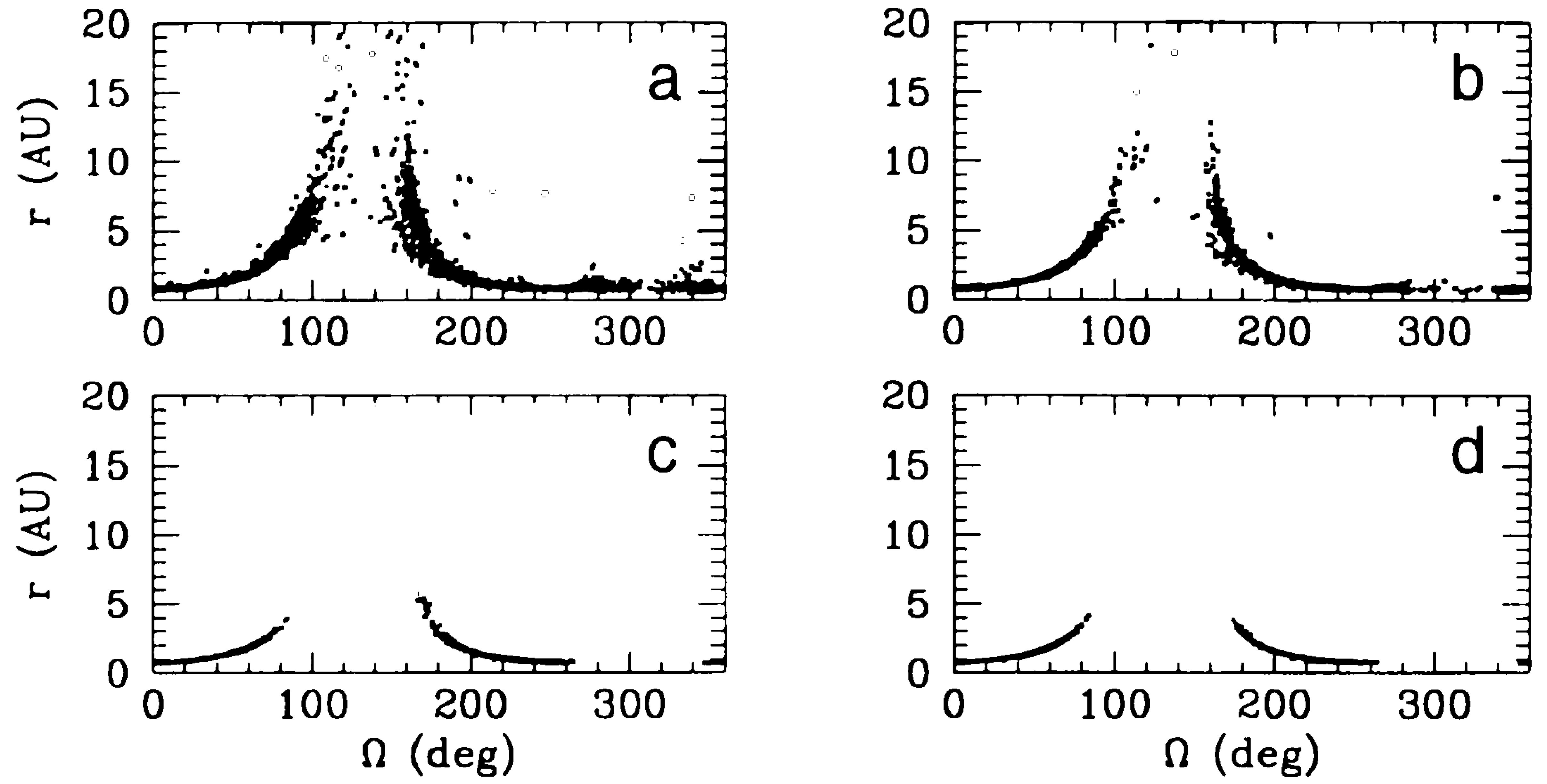

Figure 1. Distribution of ecliptic-plane crossings for particles ejected from 1P/Halley. r is the heliocentric distance and Ω denotes the ecliptic longitude measured from the vernal equinox.

2. Ecliptic-plane crossings

In order to study the main features of Halley-type meteoroid streams we consider a model in which s particles are ejected from a parent comet on the Sun-facing hemisphere during each of N perihelion passages. The ejection velocities are assumed to be isotropic over this hemisphere and are randomly distributed in the interval $(0, V)$ according to the triangle law. We follow the dynamical evolution of each particle for N revolutions of the comet including all planetary perturbations.

Figure 1 shows the distribution of ecliptic-plane crossings for particles ejected from 1P/Halley. Figures 1a, 1b and 1c are based on s=10, V=100 m s^{-1} and N=300, 200 and 100. Figure 1d shows the same distribution for s=10, V=20 m s^{-1} and N=100. The distributions are broadly similar, showing that the stream crosses the Earth's orbit at two points corresponding to the two observed showers (the Orionids and η-Aquarids). The existence of two showers associated with 1P/Halley is thus a direct consequence of planetary perturbations.

We note that the distribution of ecliptic-plane crossings has a narrow, almost linear structure. Although most of the ejected particles are not librating about exact mean-motion commensurabilities, the positions of the ecliptic-plane crossings are nevertheless mainly determined by the system of resonances due to planetary perturbations. We have obtained a very similar picture on the basis of mappings taking into account only the main periodical perturbations (Emel'yanenko 1992b), suggesting that differential secular effects are also unimportant in determining the general features of the r-Ω diagram. The present work shows that the location of this line is only weakly dependent on initial conditions. Variations of the ejection velocity up to 100 m s^{-1} do not significantly change this picture nor does it change rapidly with time.

Investigations of meteoroid streams associated with other Halley-type comets show similar characteristics. We conclude that despite the complicated struc-

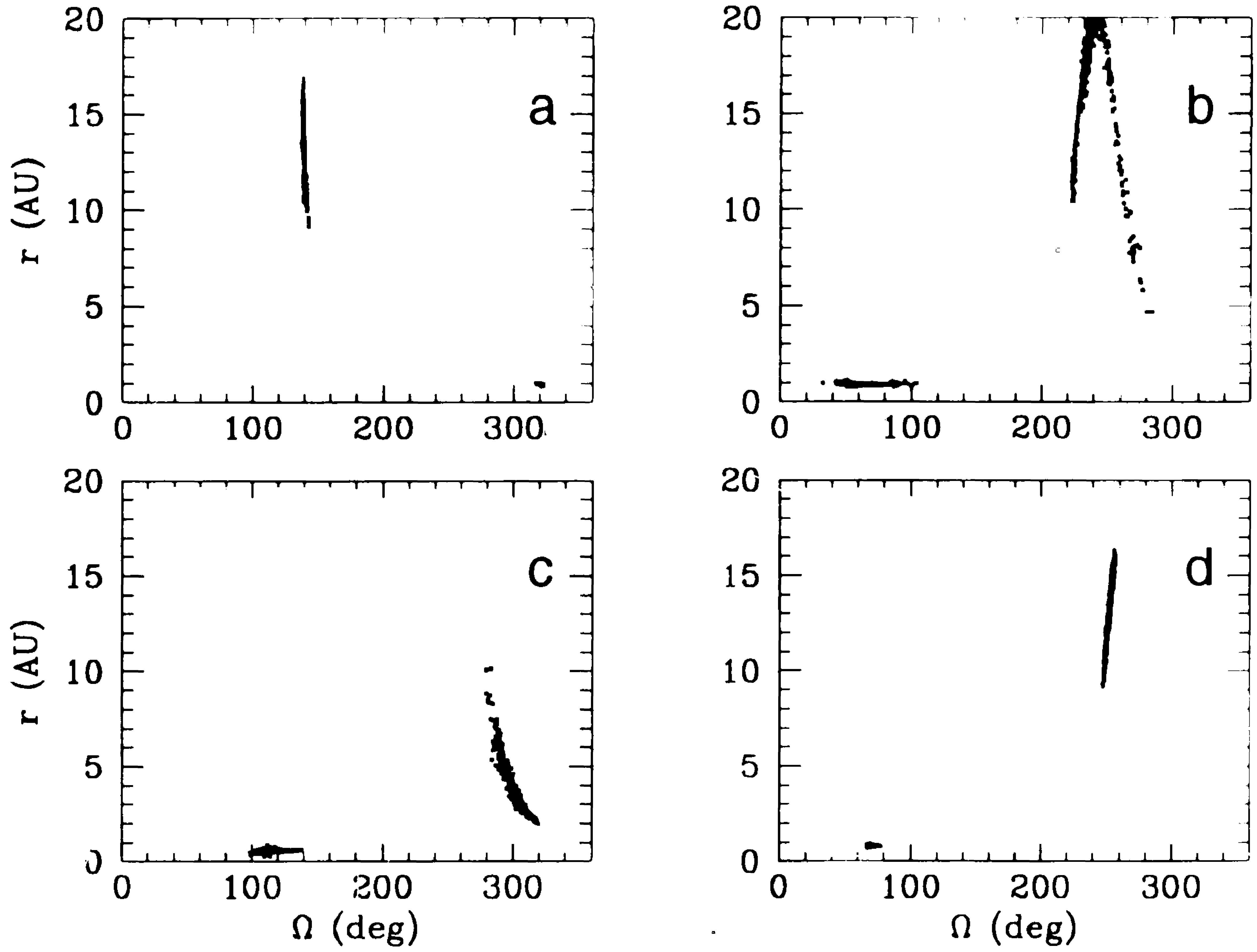

Figure 2. Distribution of ecliptic-plane crossings for particles ejected from (a) 109P/Swift-Tuttle, (b) 55P/Tempel-Tuttle, (c) 23P/Brorsen-Metcalf and (d) 12P/Pons-Brooks.

tures of old Halley-type meteoroid streams, their general features may be understood as a consequence of planetary perturbations. Figure 2 shows distributions calculated for particles ejected by (a) 109P/Swift-Tuttle (Perseids), (b) 55P/Tempel-Tuttle (Leonids), (c) 23P/Brorsen-Metcalf, and (d) 12P/Pons-Brooks, assuming $V=100\,\mathrm{m\ s^{-1}}$, $N=75$ and $s=10$. The parameters have been chosen only to illustrate the distribution of ecliptic-plane crossings for each meteoroid stream. The real widths and lengths of these structures will of course depend on details of the cometary ejection process and on the parent comet's physical and dynamical evolution. Studies of the detailed structure and evolution of meteoroid streams thus provide a powerful new tool to address some of these questions.

3. Resonances produce storms

The presence of librations means that the rate of dispersal of the meteoroid stream is much less than that under chaotic conditions (Emel'yanenko 1988). This is illustrated in Figure 3, which shows the ecliptic-plane crossings for two parts of a hypothetical meteoroid stream close to the orbit of the Lyrids, each containing 100 meteoroids. The motion has been calculated including all planetary perturbations and the results are shown after $N=32$ revolutions. The initial conditions for (a) and (b) are the same except that in model (a) the semi-major axes are uniformly distributed in the range (14.97, 15.47) AU (for

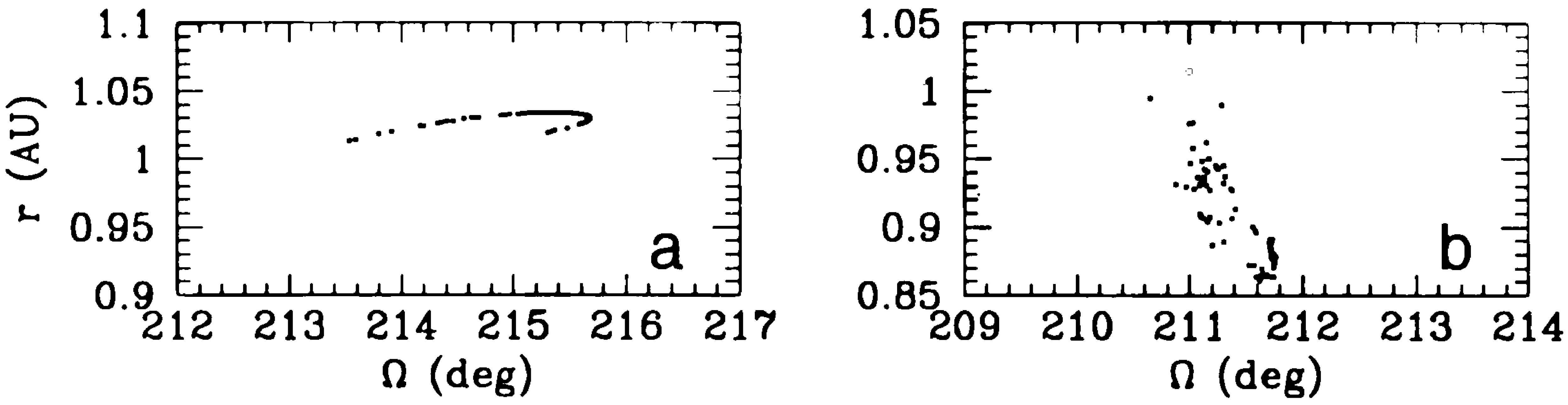

Figure 3. Ecliptic-plane crossings for meteoroids with initial orbits close to that of the Lyrids. Note the extreme concentration of particles in the librating model (a).

which the mean value 15.22 AU corresponds to an exact 1:5 commensurability with Jupiter), and in (b) they are uniformly distributed between the 1:5 and 1:6 mean-motion resonances in the range (15.90, 16.40) AU.

These calculations show that the effect of libration is to confine the distribution of ecliptic-plane crossings to an extremely narrow region. Resonant streams are thus very concentrated in space and may lead to hazardous meteor storms similar to those associated with recently ejected particles (Beech et al. 1995). A remarkable example of such a dynamical condensation appears to be the stream associated with the annual Lyrid shower (Emel'yanenko 1990), which although usually broad and weak has been observed to show a narrow, dense 'storm' component. Librating particles ejected from Halley-type comets may produce substreams capable, despite their age, of causing dangerous meteor storms.

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