CONTINUING EVIDENCE OF AN IMPULSIVE COMPONENT OF OORT CLOUD COMETARY FLUX

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ABSTRACT

An impulsive component of new Oort cloud cometary flux has previously been identified using data from the Catalogues of Cometary Orbits. That data is augmented by 1/3 in the latest Catalogue. The binomial probability that the previously identified overpopulated region of the celestial sphere would continue to be overpopulated as much or more in the new data if the distribution were truly random is 0.009. In addition, correlations between orbital elements that are characteristic of an impulse remain statistically significant. The geometry of the overpopulated band is inconsistent with a stellar impulse but may be compatible with a bound Jovian mass solar companion.

Key words: comets, dynamics.

1. THEORY

1.1. Galactic Tidal Perturbation

Using 11th Catalogue data (Marsden and Williams, 1996), Matese et al. (1999) (cf. Heisler and Tremaine, 1986; Wiegert and Tremaine, 1999) describe the theoretical arguments demonstrating that the dominant dynamical mechanism that makes outer Oort cloud comets observable is the quasi-adiabatic galactic tidal torque. This is manifest in the distribution of cometary major axis orientations which has pronounced deficiencies at the galactic poles and equator. Additional characteristics of this dominance are three pairs of correlations between orbital elements - the perihelion distance, q, the inverse of the original semimajor axis, x, and the sign, S, of the scalar product between the galactic tidal torque and the observed angular momentum direction. S is a combination of the three orientation angles of the orbit (Eq. 14 in Matese and Lissauer (2002)). To allow a comet to be recognized as coming from the outer Oort cloud, q must be reduced from beyond the loss circle barrier to observable values in a single orbit (rms energy changes due to planetary impulses on Oort cloud comets are $\Delta x > 30$ for $q < 15$ AU, (Fernandez, 1981)). This will most readily occur for near-parabolic comets for which the angular momentum is $\propto \sqrt{q}$. A single-orbit change in the angular momentum due to the tidal perturbation is $\propto x^{-7/2}$ while the *in situ* flux of Oort cloud comets increases rapidly with x. Therefore comets that "just barely" make it inside the observable region will preferentially have larger values of q, larger values of x and negative S. Detailed modeling of this dynamical problem confirms that we should expect three pairs of correlations between large-q, large-x and negative values of S (Matese and Lissauer, 2002).

1.2. Impulsive Perturbation

If a comet is impulsed, the torque from the impulse must be appropriately combined with that due to the galactic tide in calculating single-orbit angular momentum changes. Comets with values of x that are slightly too large to allow the tide alone to reduce q from beyond the loss circle to within the observable region, can be made observable if the impulse assists in reducing the angular momentum. Since weak impulses have larger scattering cross sections, they will be more numerous than strong impulses. Therefore we can understand the results of modeling (Matese and Lissauer, 2002) which indicate that along the path of an impulsive perturber a larger observed comet flux should occur, and that this impulse-enhanced flux should preferentially have larger-q, larger-x and more negative values of S than the flux from negligibly-impulsed comets.

2. OBSERVATIONS

The cometary orbital data we analyze here are taken from the 14th Catalogue of Cometary Orbits (Marsden and Williams, 2001).

2.1. Energy Cut

We select all comets whose original energy, $x \equiv 10^6 \mathrm{AU}/a_{orig}$, is less tightly bound than $x = 100$, the value first chosen by Oort (1950) to denote new comets from the cloud. We do not exclude nominally unbound comets ($x \leq 0$). These are most likely truly bound but have outgassing effects that have not been accounted for.

2.2. Quality Class

The orbits with energies listed in the catalogues are subdivided into 4 classes of decreasing quality, 1A, 1B, 2A and 2B. For our purposes, all of the orbital elements are accurately known excepting the original energy, i.e., the quality class label is mainly a statement about formal uncertainties in the comet's original energy (Marsden et al., 1978). This does not imply that errors due to outgassing effects are uniformly smaller as we go from class 2B to class 1A. We choose to include quality classes 1A and 1B in this analysis yielding 82 comets from the 11th Catalogue and 109 comets from the 14th Catalogue. This is a compromise between rejecting poorer data that degrades the correlation analyses described below and increasing the number of comets and, potentially, the statistical significance. We shall show that the data are good enough to make evident the characteristics that demonstrate the dominance of the galactic tide. Of more interest is the question of whether the quality of the data is sufficient to infer a weak impulsive component.

3. OBSERVATIONAL SELECTION EFFECTS

A self-evident selection effect is that comets with larger values of q are more difficult to detect since their coma will be less and their increased distance further reduces their apparent magnitude. This will serve to *reduce* the evidence of an impulse which preferentially is seen in large-q comets. Another standard selection effect is associated with a preponderance of observers in the northern hemisphere who have a lessened ability to see the sky at equatorial declinations $\delta < -30°$. Although this effect is real, its statistical significance is insubstantial for this sample since 25 comets have perihelia in the π steradian solid angle centered on the south equatorial pole while 84 comets have perihelia in the complementary 3π solid angle (see Figure 7 below). Yet another bias occurs because the outgassing that is associated with nominally hyperbolic original orbits is known to be correlated with small perihelion distances (Marsden et al., 1978). This effect will not spuriously produce evidence of an impulsive component since an impulse will manifest itself in large-q, large-x comets. The most thorough investigation of observational selection effects for this data has been done by Horner and Evans (2002).

4. OBSERVATIONS

4.1. Evidence That The Galactic Tide Dominates

In Figure 1 we show the distribution of aphelia latitudes, B, using 14th Catalogue data. A random distribution would be uniform in $\sin B$. The double-humped distribution is characteristic of the galactic disk tide.

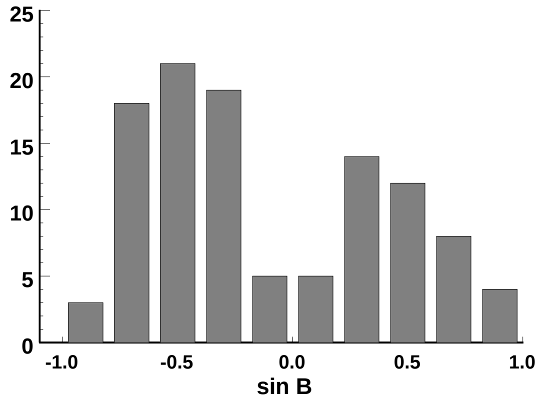

Figure 1. Observed distribution of the galactic latitude of aphelia, B, of all class 1 comets with $x < 100$ listed in Marsden and Williams (2001).

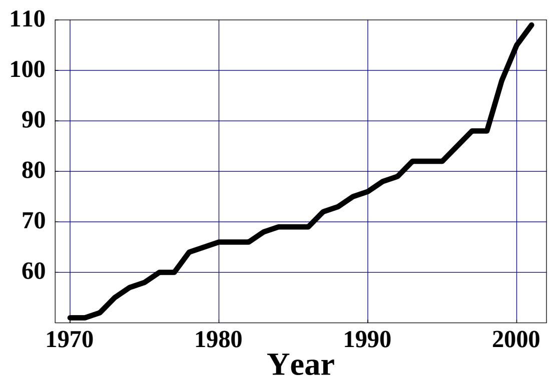

Figure 2. Cumulative number of class 1 new comets as a function of the comet year identification.

Figure 2 shows the cumulative number of class 1 new comets as a function of time. A recent increase in the observation frequency can be partially attributed to the success of new observing programs such as LINEAR and NEAT in detecting large-q comets (Figure 3). The most recent comet year identification listed in the 11th Catalogue (published in 1996) and used by Matese et al. (1999) was 1993.

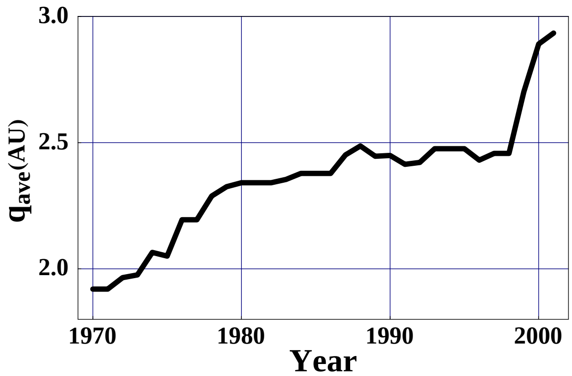

Figure 3. Cumulative average perihelion distance.

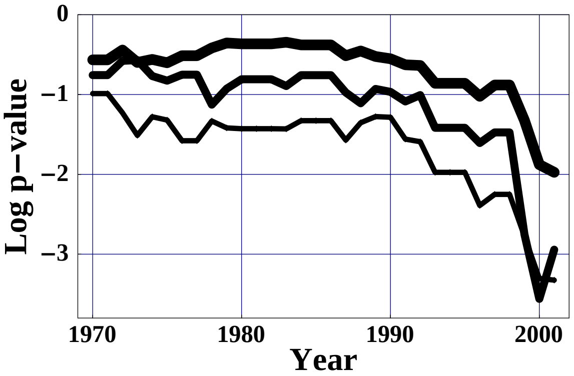

Figure 4. Cumulative Kendall rank-correlation p-values. These are measures of the likelihood that we would have as much or more correlation between the data if in fact the variables were unassociated. In order of increasing line thickness, large-q $\leftrightarrow$ large-x, large-q $\leftrightarrow$ $\mathrm{negative}\ S$*, large-x $\leftrightarrow$* $\mathrm{negative}\ S$

Further evidence of the dominance of the galactic tide is obtained by investigating the prediction of the threefold association between q, x and S described in Sec. 1.1. We use the Kendall rank-correlation test (*Mathematica*, 1999) to test the null hypothesis that the data are a sample of a population with unassociated orbital elements. For each comet the values of these variables are ranked. A ranked procedure is appropriate because of the undue influence that would occur with the handful of extreme values of negative x for the hyperbolic comets in unranked tests. The Kendall procedure is chosen because of its ability to handle ties in rankings for x and S.

Figure 4 shows the p-values for the three pairs of variables. These are measures of the likelihood that we would have as much or more correlation between the data if in fact the variables were unassociated. A notable decrease in the p-values can be attributed in part to increased numbers and to a marked increase in the average value of cometary q being detected in recent times (Figure 3). The three independent p-values found are statistically significant, with their combined product being $p_c = 6\ 10^{-9}$. The probability that the combined product would be smaller than p_c if the elements were unassociated is given by

$$\int_0^1 du \int_0^1 dv \int_0^1 dw \quad \Theta\,(p_c - u\ v\ w)$$

$$= p_c[1 - \ln p_c + (\ln p_c)^2/2] \approx 10^{-6}.$$

We can confidently reject the null hypothesis that the comet data are sampled from a population with unassociated orbital elements. In contrast one cannot reject the hypothesis that the data sampled a population where the galactic tidal characteristics dominate. Similar comments are applicable to the latitude distribution of Figure 1 providing unambiguous evidence that the data chosen for analysis are of sufficiently high quality, and are sufficiently free from observational bias, to detect these characteristics.

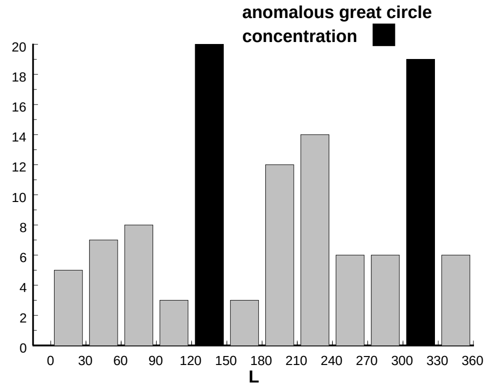

Figure 5. Observed distribution of the galactic longitude of aphelia, L. The two noted bins are anomalously concentrated.

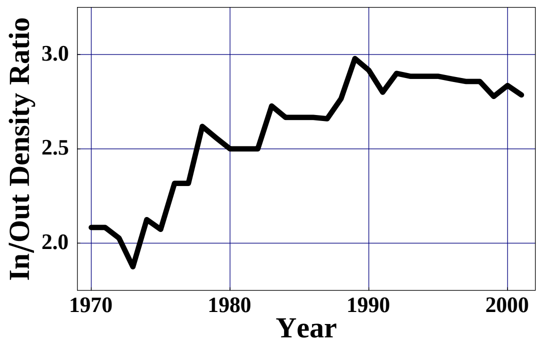

Figure 6. Cumulative annual variation of the anomalous concentration shown in Figure 5, expressed as a ratio of the number of aphelion points per unit solid angle in and out of the two indicated longitude bins.

4.2. Evidence For An Impulsive Component in the Class 1 New Comet Population

Although the galactic tide dominates in making Oort cloud comets observable at the present epoch, we now seek evidence of a weak impulsive contribution. As described in Sec. 1.2, one should look for an overpopulated region on the celestial sphere that preferentially has larger values of q and x, and more values of $S = -1$. An anomalous concentration was noted by Matese et al. (1999) in a distribution of galactic longitude of aphelia, shown here in Figure 5 using 14th Catalogue data. It is oriented along a great circle arc passing near the galactic poles and intersecting the galactic midplane at longitudes $L \approx 135°,\ 315°$. In going from the 11th Catalogue to the 14th Catalogue, 27 additional comets satisfying our data cut have been observed, and 9 of them occur in the two noted longitude bins. The binomial probability that 9 or more of 27 comet axes would fall in the predetermined longitudinal bins occupying 1/6 of the celestial sphere if in fact the axes were distributed azimuthally uniform is 0.009.

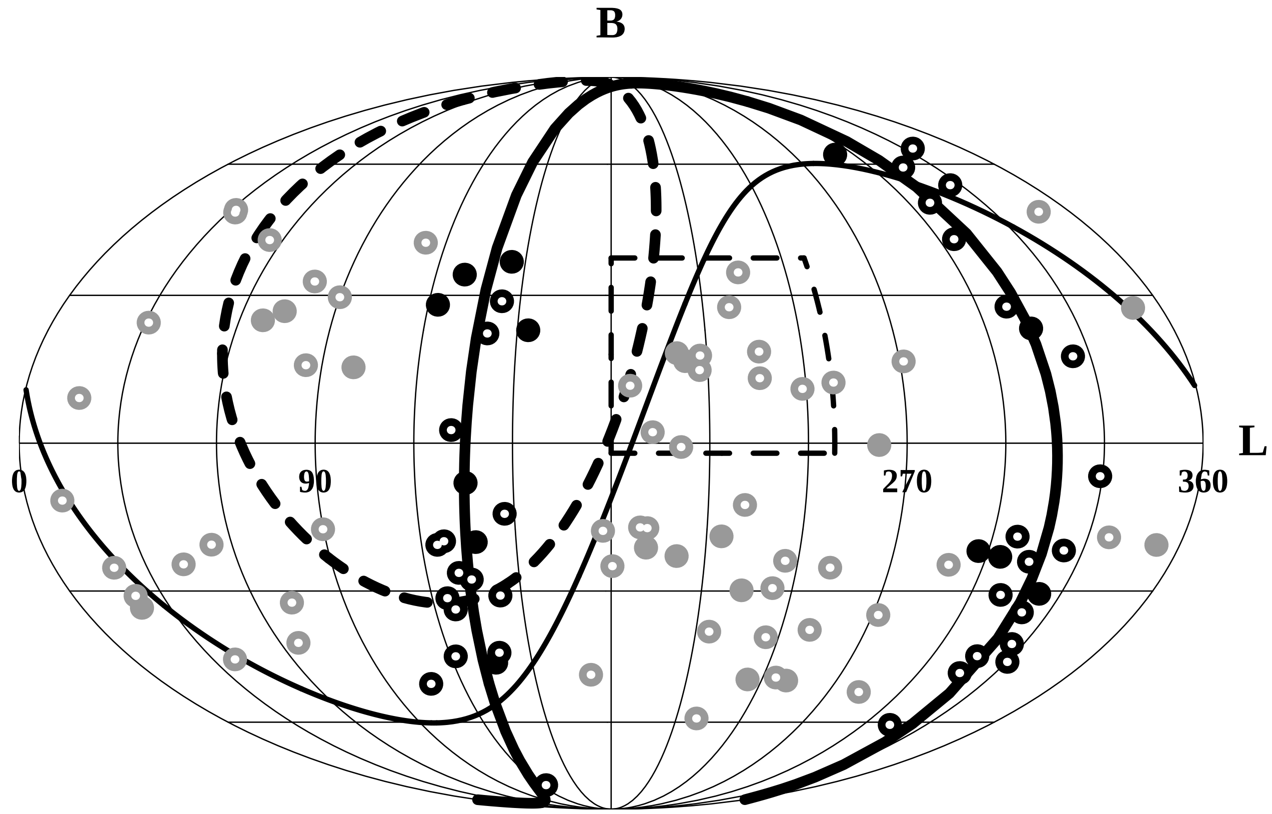

Figure 7. Distribution of class 1 new comet aphelia directions (antipodal to observed perihelion directions) on the celestial sphere in galactic coordinates. All comets identified here with black dots as being inside the great circle band fall within $17°$ of the best fit great circle plane (thick solid line which has a normal vector with orientation $B = 4°,\ L = 44°$). Inside this band are 45 comet axes, while 64 are outside. Comets outside the band are denoted by gray dots. 11th Catalogue data are indicated by small white dots. The ecliptic is the thin solid line. Interior to the thin dashed line is the concentration that Biermann et al. (1983) have identified as a weak stellar shower. A curve antipodal to the equatorial declination of $\delta = -30°$ (enclosing a region largely unavailable to observers in the northern hemisphere) is shown as a thick dashed line.

In Figure 6 we show the time dependence of the concentration. Since an impulsed component of comet flux preferentially enhances the flux at large-q (Matese and Lissauer, 2002), as observational bias against detecting large-q comets lessens, the observed concentration should remain substantive.

We have iteratively found a best-fit great circle to the new class 1 data, successively including all comets whose major axis lies within a specified angle γ of the best fit orbit plane. In Figure 7 we show the distribution on the celestial sphere of comet aphelia directions, noting comets within a band $\gamma = \pm 17°$ of the best-fit orbit plane.

Horner and Evans (2002) have concluded that neither known observational selection effects nor chance are likely to produce this concentration. They have also looked at the class 1A subset of the data and found a stronger concentration than in the entire class 1A+1B set. They did conclude that there is little motivation for continuing to explore an alternative conjecture of an impulse-produced concentration (Murray, 1999).

In Figures 8 - 10 we compare data inside and outside this band. Figure 8 illustrates the differences in the original energy distributions while Figure 9 similarly compares the distributions in q. Associations with the sign of the galactic tidal torque, S, are also shown.

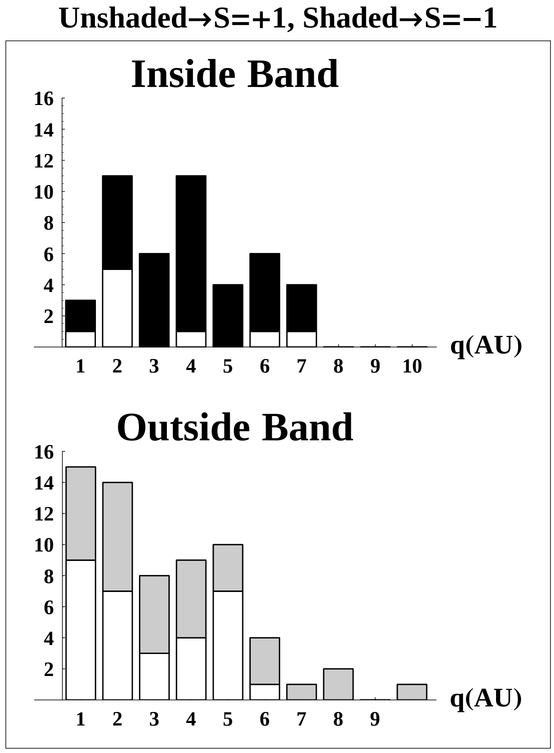

Figure 9. Observed distributions of the perihelion distance, q, separately given for comets in and out of the band illustrated in Figure 7. Distributions of the galactic tidal torque sign, S, are also shown. The bin labeled "1" includes all comets with $0 < q < 1$ AU, etc.

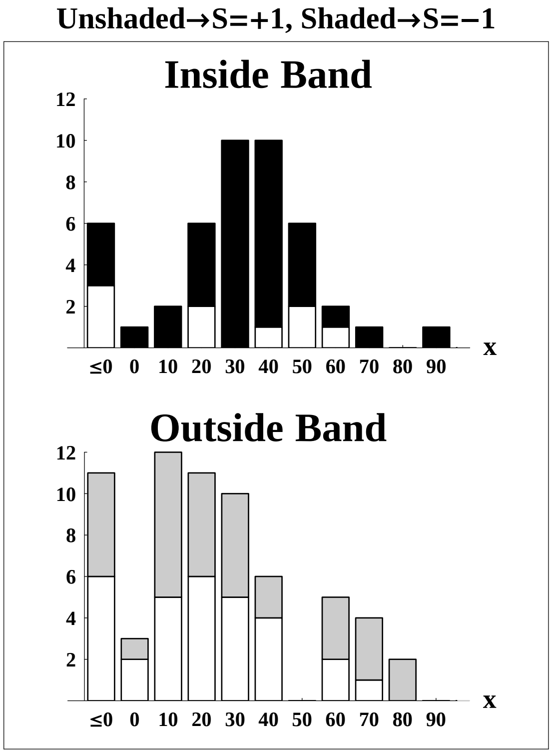

Figure 8. Observed distribution of original energy, $x \equiv 10^6\,\mathrm{AU}/a_{orig}$, separately given for comets in and out of the band illustrated in Figure 7. Distributions of the galactic tidal torque sign, S, are also shown. The bin labeled "≤ 0" includes all nominally unbound original energies, the bin labeled "0" contains all original energies 1-10, etc.

Although these distributions in Figures 8-9 appear to be samples from different populations, a statistical analysis is required to lend confidence to this visual conjecture. We then test the null hypothesis that large-q, large-x and negative S (which have been shown to be mutually associated in Figure 4) are unassociated with cometary major axes identified as being in the overpopulated band. If the overpopulated region is truly augmented by a weak impulse, it must exhibit the correlations described in Sec. 1.2. Figure 10 illustrates this. The p-values that these three elements are unassociated with major axis orientations are 0.022 (large-q), 0.008 (large-x) and 4 10^{-6} ($S = -1$). That is, these small p-values are measures of the likelihood that we would get as much or more correlation between these variables and comet axis orientations within the $\pm 17°$ band if in fact they were unassociated. These results cannot be convolved since the three variables have already been demonstrated to be mutually associated in Figure 4. Comparable statistical results are found for $12° < \gamma < 17°$.

4.3. Absence Of Evidence For An Impulsive Component In Other Comet Populations

A concentration similar to that illustrated in Figures 5 and 7 is not found in other cuts of the data. It is commonly argued that comets with intermediate values of original energies ($1000 > x > 100$) are daughters of new comets that have made only a few passes interior

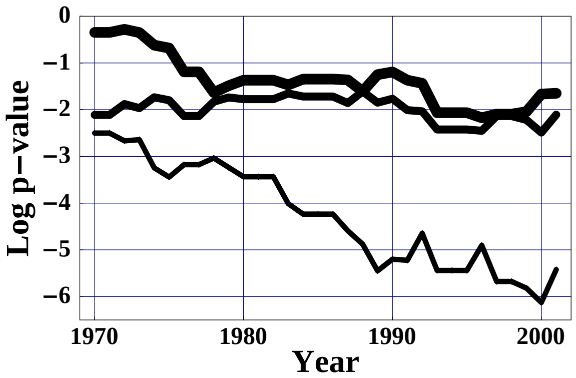

Figure 10. Cumulative Kendall rank-correlation p-values. These test the null hypothesis that negative S, *large-x and large-q are unassociated with comet major axis orientation within the* $\pm 17°$ *band. Small p-values are measures of the likelihood that we would get as much or more correlation between these variables and comet axis orientations within the band if in fact they were truly unassociated. In order of increasing line thickness,* negative $S \leftrightarrow$ *band , large-x $\leftrightarrow$ band and large-q $\leftrightarrow$ band.*

to the loss circle after arriving from the Oort cloud. But only 8 of 55 major axes of class 1 intermediate comets are in the longitude bins noted in Figure 5.

Planetary impulses of Oort cloud comets with $q < 6$ AU give rms energy changes of $\Delta x \sim 1000$ while leaving other orbital elements largely unchanged (Fernandez, 1981). Individual values of Δx are strongly dependent on q and on the inclination of the orbit to the ecliptic. Prograde orbits will have smaller relative velocities than retrograde orbits and will experience larger planetary impulses. This effect is evident in the data where the ratios of prograde to retrograde orbits of class 1 intermediate comets are 14/33 for those outside the longitude bins noted in Figure 5 and 4/4 for those comets in the bins. The corresponding ratios for class 1 new comets are 34/36 and 22/17. Comparisons of the distributions in q and S for intermediate energy comets are also different from that illustrated in Figure 9 for new comets. The maximum value of q for the 8 intermediate comets in the noted bins (2.47 AU) is essentially the same as the median value of q for the 47 comets outside the bins (2.32 AU), reversing the correlations found in the new data. That is, the intermediate samples differ from the new samples not only in energy, the defining difference, but in the distributions of other orbital elements as well. Wiegert and Tremaine (1999) give a detailed analysis in support of longstanding conclusions that “the observed energy distribution of long period (> 200 y) comets is incompatible with the expected steady-state distribution unless many new comets are destroyed before their second or subsequent passage.” Therefore an explanation for the absence of the characteristic imprints of an impulse on the intermediate energy data sample may well be tied to the “fading” problem.

There are also 19 class 2 new comets with a median perihelion distance of 1.12 AU that are not concentrated in the band. The absence of the concentration here could be due to the substantially smaller values of q than are found for class 1 new comets.

5. SUMMARY

Using 14th Catalogue data, characteristic imprints of the dominant galactic tidal perturbation of the outer Oort comet cloud can be inferred at statistically significant levels. This suggests that the data selected are of sufficiently high quality and sufficiently free of observational bias to search for evidence of a weak impulsive contribution. A previously detected overpopulated region of cometary major axes continues in the new data. The binomial probability that the new data would be overabundant at the detected level, or more, is 0.009. Equally important is the continued evidence of orbital element correlations that is indicative of a weak impulsive contribution. The geometry of the anomalously concentrated band is inconsistent with a high-speed stellar impulse (Matese and Lissauer, 2002), but may be compatible with a Jovian mass bound companion to the Sun (Matese et al., 1999). If such objects are common in single star systems they will not necessarily be an important factor in the formation of planetary systems or trans-planetary comet belts (Collander-Brown et al., 2000).

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