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A criterion to classify asteroids and comets based on the orbital parameters

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ABSTRACT

The classification criterion between asteroids and comets has evolved in recent decades, but the main distinction remains unchanged. Comets present gas and dust ejection from the surface at some point of their orbits, therefore, these objects are considered to be active. On the other hand, asteroids do not show any kind of large scale gas and dust ejection, they are inert. Nevertheless, this classification scheme is impractical when we have more than 500,000 asteroids already discovered. In addition, comets are not active all along their orbits. In order for a comet to display activity at present or in the recent past in the inner region of the Solar System (heliocentric distance <2 AU), the cometary orbit must be unstable in the time scale on the order of ten thousands of years; otherwise, the object should have completely consumed its volatile component. Close encounters with the most massive planets is the only mechanism that could produce "macroscopic" instabilities on a short time scale. The macroscopic changes in the orbital elements can be detected in a numerical integration of the dynamical evolution of the object over a time scale of several thousand years. This procedure to identify asteroids in cometary-like orbits is also impractical because it would require months of computing time. Therefore, a classification scheme based on the orbital elements to identify the border cases between the asteroid and comet populations is urgently required.

We present a criterion to classify asteroids and comets and to find the border case based on the Tisserand's parameter, the Minimum Orbital Intersection Distance (MOID), and considering some information regarding the aphelion and perihelion distances. Objects in mean-motion are disregarded. After applying a filter to the sample of over half a million asteroids already discovered to select the precise orbits and to the sample of 487 short-period comets, we apply the proposed classification criterion. The resulting sample consists of ~331 Asteroids in Cometary Orbits (ACOs). The ACOs are further classified in subclasses similar to the cometary classification. There are 436 Jupiter Family Comets and 203 ACOs of the Jupiter Family type. This new criterion is more strict that the criteria used by other authors to identify ACOs; nonetheless, with the new criterion we ensure that the ACOs have a chaotic dynamical evolution similar to the periodic comets. The discovered dormant or extinct comets seems, if they exist at all, to be a small fraction of the active comets.

We also analyse the available photometric data of ACOs to identify possible large brightness variations. Among the sample of ACOs, there is only one object with brightness variations typical of an active comet: 174P/(60558) Echeclus. But this object has already been double classified as asteroid and comet.

1. How are asteroids and comets distinguished?

Comets present gas and dust ejection from the surface at some point of their orbits, therefore, these objects are considered to be active. Meanwhile asteroids do not show any kind of large scale gas and dust ejection, they are inert. Nevertheless, this classification scheme is impractical when we have more than half a million asteroids already discovered. In addition, comets are not active all along their orbits. Therefore, in order to be sure that an object is not active, we should follow the object at many orbital positions. Hence, this classification is not useful for the present data set.

The dynamical evolution of known periodic comets are very chaotic (see *e.g.* Tancredi, 1995); the cometary orbits are unstable in the time scale on the order of a few thousands of years. Comets which display gaseous activity at present or in the recent past, in the inner region of the Solar System (heliocentric distance <2 AU), suffer frequent changes in the perihelion distance (q)

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(Tancredi and Rickman, 1992). Otherwise, an object in a low-q orbit should have completely consumed its volatile component close to the surface.

Close encounters with the more massive planets is the only mechanism that could produce “macroscopic” instabilities of the cometary orbits on a time scale on the order of centuries; in particular close encounters with the giant planets could produce jumps in perihelion distance. The macroscopic changes in the orbital elements and the close encounters with the planets can be detected in a numerical integration of the dynamical evolution of the object over a time scale of several thousand years. As it will be shown later, this procedure to identify asteroids in cometary-like orbits is also impractical, because the numerical integrations require a considerable amount of computing time.

Bottke et al. (2002) have pointed out that: “Several extinct comet candidates have been examined spectroscopically (Luu, 1993; Hicks et al., 1998, 2000a,b; Rabinowitz, 1998; Rabinowitz and Hicks, 1998). In general, results from these studies show that extinct comet candidates have featureless spectra with flat to modest red slopes spanning the dynamic range between C- to D-type asteroids. These features are consistent with the spectral diversity of cometary nuclei (Luu, 1993) and of Trojan bodies (Jewitt and Luu, 1990).” More recent photometric and spectroscopic studies of extinct comet candidates (see *e.g.* Fernández et al., 2005; Licandro et al., 2006, 2008; Alvarez-Candal and Licandro, 2006; DeMeo and Binzel, 2008; Alvarez-Candal, 2013) have reached similar conclusions. Therefore, it is also difficult to identify a non-active comet based on spectroscopic observations, since there are many asteroids with similar spectra.

Hence, a classification scheme based on the orbital elements to identify the border cases between the asteroid and comet populations is required. These criterion should be fast and simple to apply to the large population of known asteroids and comets.

After the identification of the border cases; *i.e.* Asteroids in Cometary Orbits (ACOs) and Comets in Asteroidal Orbits (CAOs); we could discuss whether these are a new population of objects or these are different appearance of already known populations. In the case of ACOs, we would like to know if these objects are dormant or extinct comets or they are asteroids escaping from the main belt into cometary-like chaotic orbits. What are the end-states of periodic comets? How many ACOs are there? In the case of CAOs, there are also many open questions: what is the origin of their “activity”? Are there frozen volatiles in the outer part of the asteroid main-belt?

In this work we build a criterion to classify asteroids and comets and to find the border cases. In Section 2 we present some basic definitions of relevant dynamical parameters which will be used in the classification. The data sets for the orbits of asteroids and comets are presented in Section 3. The classification of comets is described in Section 4 and the dynamical evolution of these objects is presented in Section 5. Meanwhile, the classification of asteroids is described in Section 6, and the discussion about the validity of the adopted criterion in Section 7. In Section 8, we analyse the available photometric data ACOs to identify possible large brightness variations, and hence activity. The implications of the results and a comparison with previous studies are discussed in Section 9. The conclusions are presented in Section 10.

2. Basic definitions

2.1. Tisserand’s parameter

The three-body problem considers three mutually interacting masses μ_1 (the Sun), μ_2 (the planet), and μ_3 (a small body). In the restricted three-body problem (RTBP), μ_3 is taken to be small enough, so that it does not influence the motion of μ_1 and μ_2.

In the RTBP, it is possible to define the Jacobi integral (C_J) in terms of the orbital elements of the massless particle. For a small μ_2 and a large planetocentric distance of the particle, the Jacobi integral is transformed into Tisserand’s parameter, defined as:

$$T = \frac{a_P}{a} + 2\sqrt{\frac{a}{a_P}(1-e^2)}\cos i = 2\left(\frac{a_P}{q+Q} + \sqrt{\frac{2qQ}{q+Q}}\cos i\right) \qquad (1)$$

where a_P is semimajor axis of the circular orbit of μ_2 around μ_1, a is the semimajor axis of the orbit of μ_3 around μ_1, e is the eccentricity, i is the inclination of the orbit of μ_3 respect to the orbital plane of the orbit of μ_2 around μ_1, q is perihelion Q the aphelion distance.

2.2. Minimum Orbital Intersection Distance

The Minimum Orbital Intersection Distance (*MOID*) is defined as the minimum distance between two orbits. The method to calculate the *MOID* is described in the Appendix A (Supplementary material).

Orbits with $T > 3$ do not cross the orbit of the planet, and therefore they cannot approach closer than a certain limit. Hence, there is a minimum MOID ($MOID_{min}$) for a given value of T, if $T > 3$. In Appendix A we give an explicit expression to compute $MOID_{min}$ as a function of T. There is a forbidden region in the T–$MOID$ phase space for $T > 3$. For a given T, $MOID$ values smaller than $MOID_{min}$ are not possible.

2.3. Hill’s radius

In the three body problem, the Hill’s sphere of a planet corresponds to the volume centred on the planet for which its gravitational attraction is larger than the Sun’s tidal attraction; thus, the perturbations to the heliocentric orbital elements are more significant inside the Hill’s sphere. The Hill’s radius is given by

$$R_H = a_P\left(\frac{1}{3}\frac{M_P}{M_P+M_S}\right)^{1/3} \qquad (2)$$

where a_P is the planet semimajor axis, M_P its mass, and M_S the mass of the Sun.

The Hill’s radii (in AU) of the giant planets are: Jupiter – 0.355; Saturn – 0.436; Uranus – 0.469; Neptune – 0.776.

2.4. Resonances

Although an object could have a small *MOID* respect to a planet, close encounters might not occur if the object is close to a mean-motion resonance to the planet.

Mean-motion resonances are characterised by two small integers p and q, which define the order of the resonance. In a mean-motion resonance the following condition must be fulfilled: $n'(p+q) - np \approx 0$, where n' and n are the mean motion of the perturbing planet and the massless particle, respectively. The semimajor axis ($a_{p:q}$) at the centre of the resonance is obtained from:

$$a_{p:q} = \left(\frac{p}{p+q}\right)^{2/3} a_P \qquad (3)$$

In Appendix B (Supplementary material) we describe the method to compute the width of the resonance in terms of the semimajor axis and as a function of the eccentricity for different types of resonances, as described by Murray and Dermott (1999).

Table 1 presents the list of resonances to be considered in the selection process described in Section 6. The semimajor axis at the centre of the resonance is listed, as well as the maximum libration in semimajor axis computed with the equations presented in Appendix B. For those resonances close to the orbit of Jupiter, *i.e.*