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The parent of the Quadrantid meteoroid stream

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ABSTRACT

The Quadrantid meteor shower is one of the major showers that produces reliable displays every January. However, it is unique amongst the major showers in still not having its parent uniquely identified. One of the reasons for this may be because the stream, and presumably the parent, lies in a region of the Solar system where near-resonant motion with Jupiter, coupled with potential close encounters, is possible. Such a combination can lead to a rapid dynamical evolution of an orbit. In particular, it may be possible that the orbit of the parent both satisfies the condition for a close encounter and is in resonant motion, while most of the meteoroids cannot satisfy both conditions. This results in the parent evolving away from the bulk of the stream.

To date, two suggestions have been made regarding possible parents for the Quadrantid stream, these being Comet 1491 I and Comet 96P/Machholz. The argument in favour of the first named being the parent is because of the general similarity between the orbits around 1491. The argument for comet 96P/Machholz being the parent is based on the similarity in orbital evolution coupled with a similarity in orbits phase-shifted by 2000 yr. In this paper we suggest that on both counts asteroid 5496 (1973 NA) is more similar to the Quadrantids, and that even if 5496 is not the actual parent in the strict sense that meteoroids are currently being ejected, it is either likely to be a fragment of the parent or the dormant remains of the parent.

Key words: comets: individual: 1491 I – comets: individual: 96P/Machholz – meteors, meteoroids – minor planets, asteroids.

1 INTRODUCTION

The Quadrantid shower is one of the regular and major events in the meteor observer's calendar, producing displays on January 3 and 4 each year with a maximum zenithal hourly rate (ZHR) of around 100. The peak activity period is quite short, being generally less than a day (Shelton 1965), and this, coupled with general bad weather in January, means that observations are not as plentiful as might be expected for such a prolific stream, although the number of Quadrantid meteoroids with well-determined orbits is fairly high, Wu & Williams (1992) locating 118 such orbits in the records of the IAU Meteor Orbit Data Center at Lund. The Quadrantid shower was identified as a regular stream as early as 1835 (Fischer 1930; Lovell 1954), and so ranks as one of the first identified streams. However, despite its strength and regularity in the current epoch, no records of the Quadrantids earlier than the beginning of the 19th century appear to exist, even though Chinese and Japanese documents date back for two millennia (Hasegawa 1993) and recordings are plentiful for other well-known meteor showers such as the Perseids, the Leonids and the Lyrids. Murray, Hughes & Williams (1980) investigated a fairly simple model of the stream by numerically integrating the motion of 10 hypothetical meteoroids equally spaced in eccentric anomaly along the mean orbit of Quadrantids. This model demonstrated that perturbations by Jupiter cause small changes in the nodal distance of the mean stream as well as in the longitude of the node, so that the Earth did not intersect the stream prior to the 19th century. This was not the first investigation to indicate that the Quadrantid stream could undergo a rapid orbital evolution; Hamid & Youssef (1963) had found that large changes in both inclination and eccentricity took place with a period of around 4000 yr, while more recent numerical integrations by Hughes, Williams & Fox (1981), Froeschle & Scholl (1982, 1986), Babadzhanov & Obrubov (1987) and Wu & Williams (1992) all show that rapid and large changes in the orbital

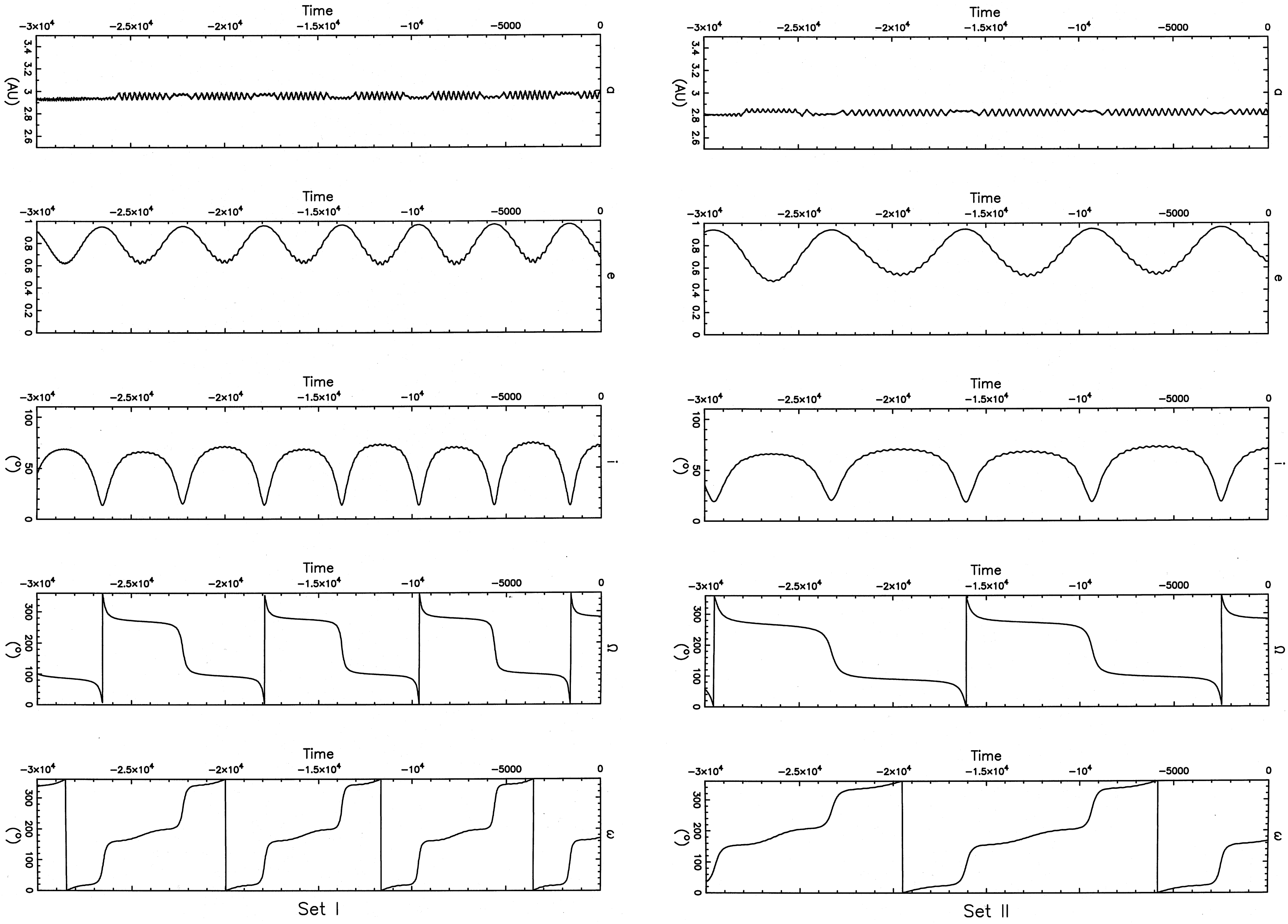

Figure 1. The changes in the indicated orbital parameters obtained by numerical integration going back in time over 30000 yr for the mean orbits of three sets of Quadrantid meteoroids, obtained by Wu & Williams (1992), and for asteroid 5496.

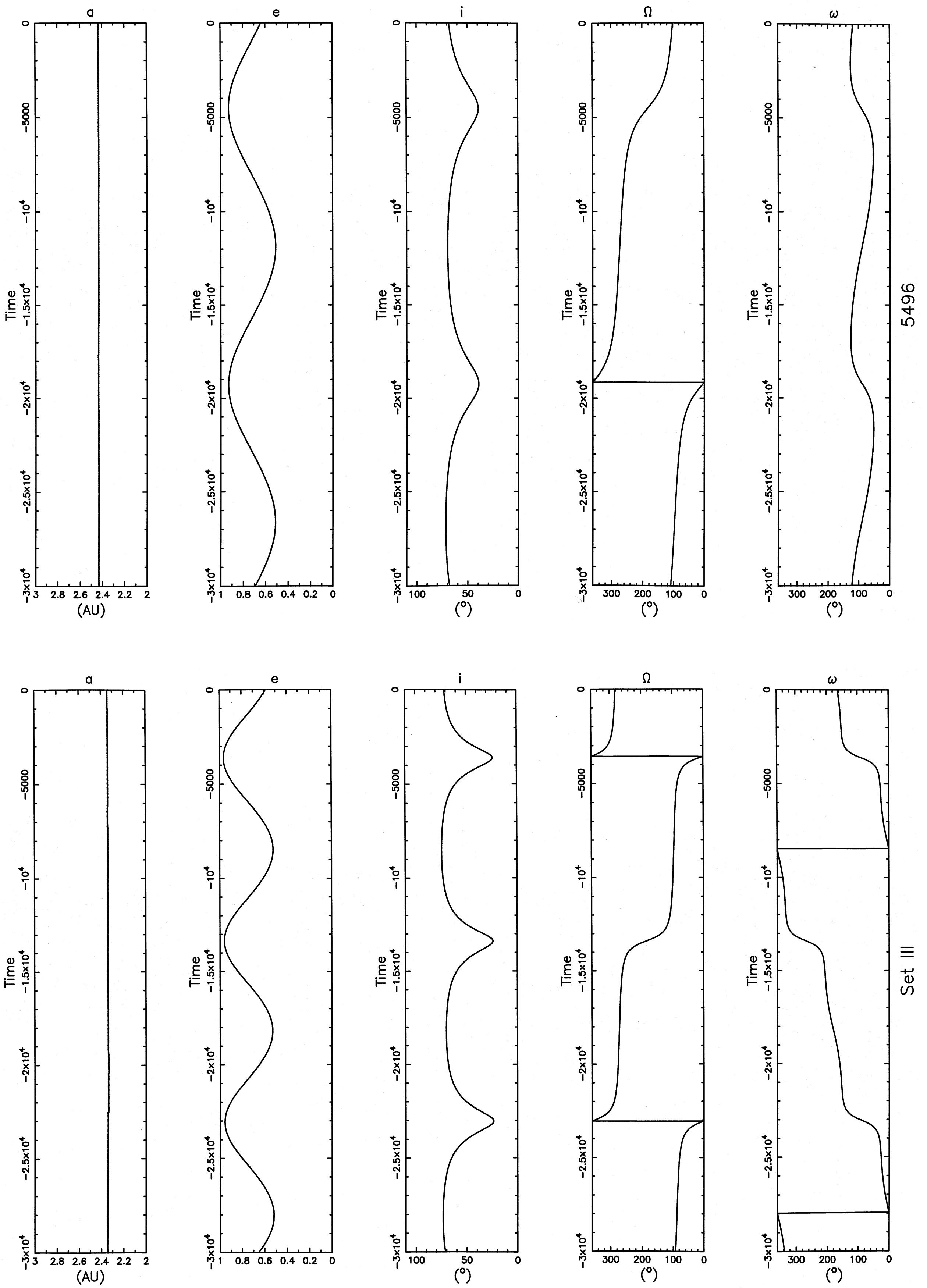

Figure 1 – *continued*

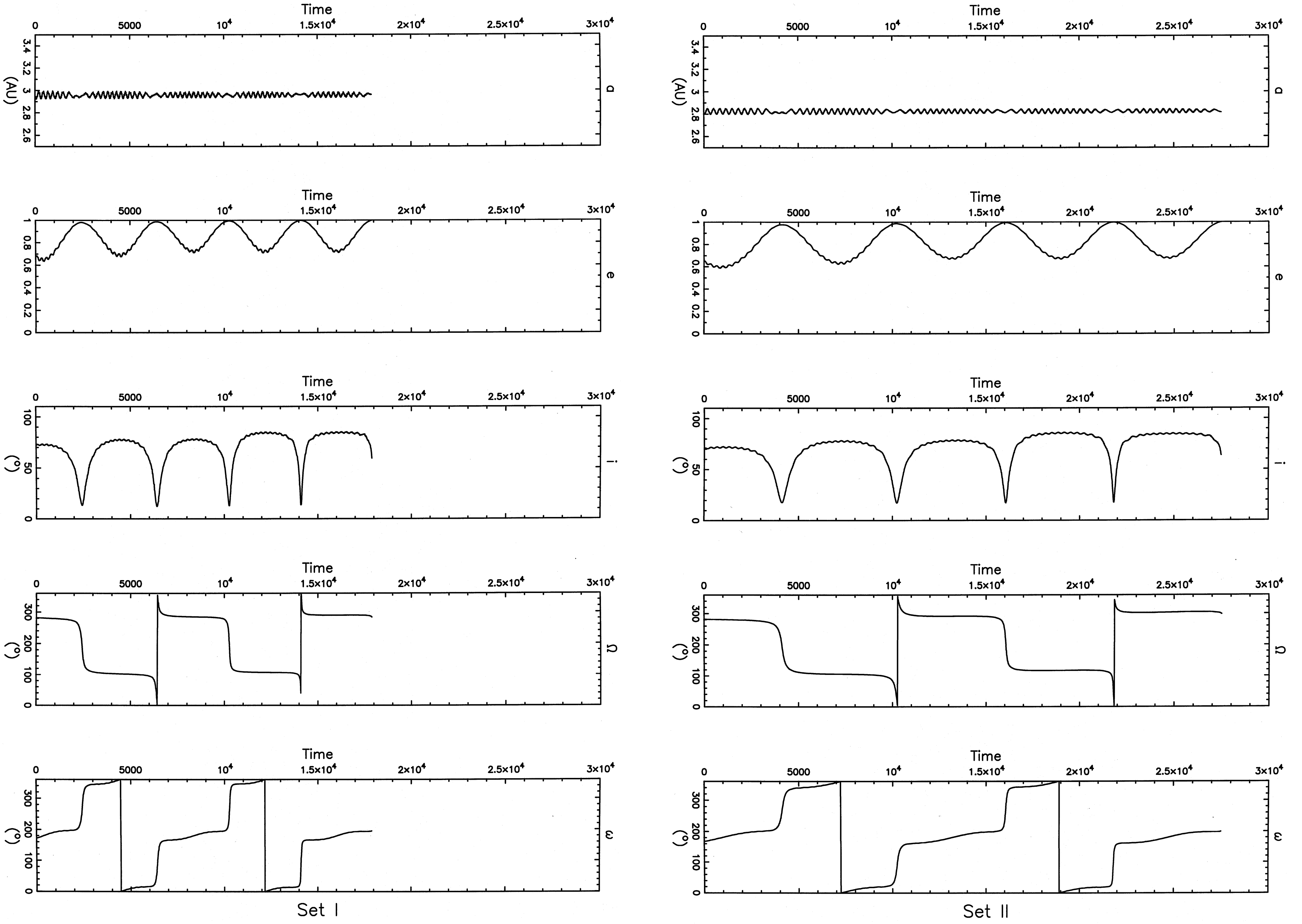

Figure 2. The same as Fig. 1, except that the integration is forward in time. Any curve stopping before 30000 yr is completed implies that the eccentricity became unity and the corresponding perihelion zero.

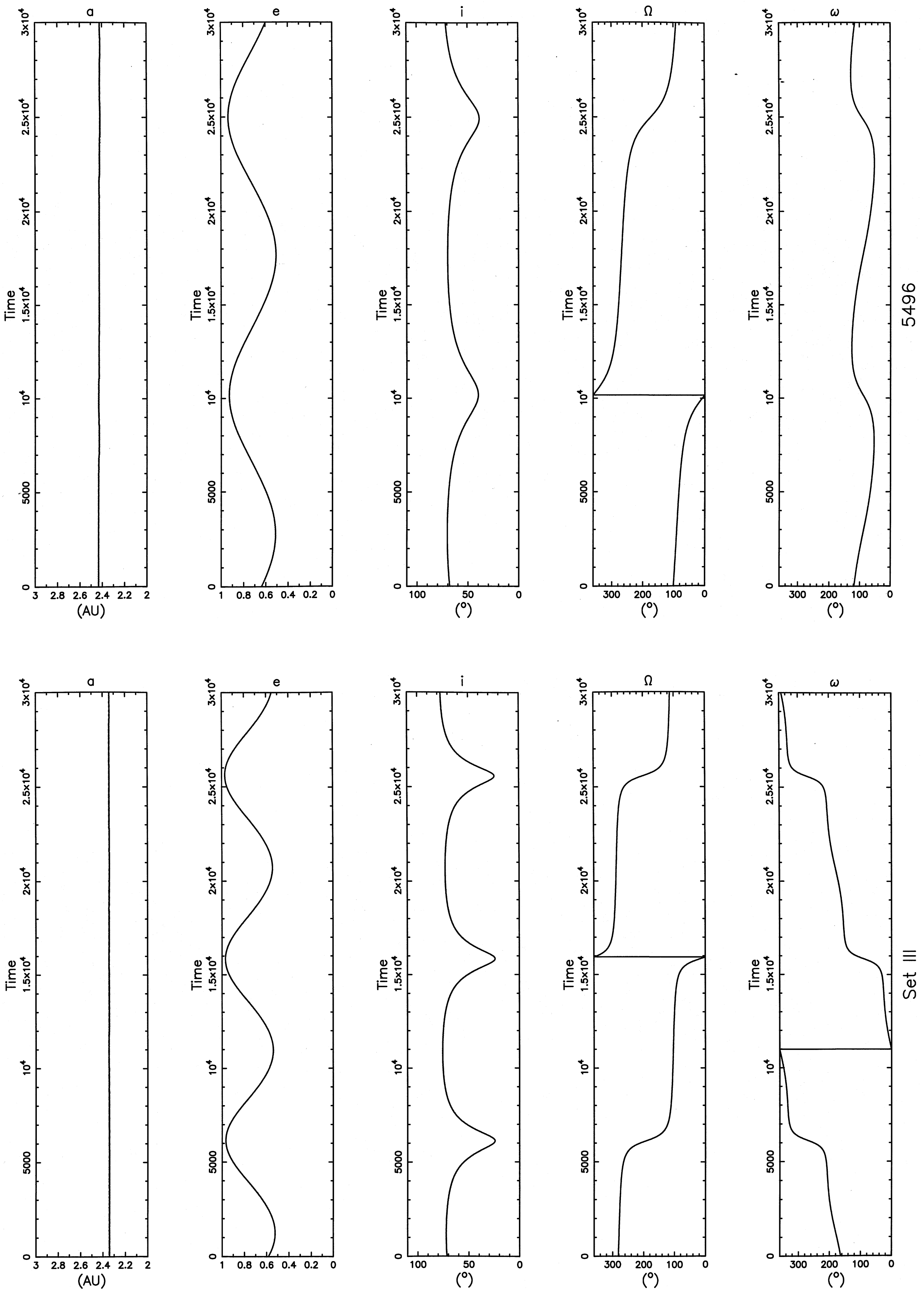

Figure 2 – *continued*

element of Quadrantid meteoroids can take place with a time-scale of a few thousand years. We have carried out further numerical integrations of the Quadrantid stream, and these are discussed later in the paper. However, Figs 1 and 2 illustrate the general behaviour that was found by all these previous integrations. The mean orbital elements of the Quadrantids at the present epoch, calculated by Wu & Williams from the orbital elements of 118 actual Quadrantid meteoroid orbits, are eccentricity $e=0.681$, perihelion distance $q=0.974$, inclination $i=71\overset{\circ}{.}4$, longitude of the ascending node $\Omega=282\overset{\circ}{.}17$, and longitude of perihelion $\omega=169\overset{\circ}{.}4$. This orbit is not significantly different from the mean Quadrantid orbit given by Poole, Hughes & Kaiser (1972), where $e=0.681$, $q=0.979$, $i=71\overset{\circ}{.}4$, $\Omega=282\overset{\circ}{.}46$ and $\omega=170\overset{\circ}{.}40$, or to the orbits used by many of the authors referred to earlier in order to carry out numerical integrations. The semimajor axis of the Wu & Williams orbit is 3.05 au (3.07 au for the Poole et al. orbit), so that the orbital period of a body moving on such an orbit is 5.34 yr. The nodal distance is 0.981 au; hence the orbit approaches to within 0.02 au of the Earth's orbit.

Our general understanding of meteoroid stream formation (see, e.g., Steel 1994 and Williams 1996) would lead us to expect that a comet should be orbiting the Sun on a very similar orbit to that of the Quadrantid meteor stream. To date, no such comet has been found. There are three possible reasons why this could be the case. First, the comet and the stream could have followed different evolutionary paths so that, even though at the stream formation stage they were on similar orbits, the stream and the parent are now on different orbits. The rapid evolution of orbits in this general location in the Solar system, already referred to above, makes this outcome very plausible; the only question to be discussed is whether or not the time-scale for this to happen is consistent with age of the stream and the comet. Secondly, the comet could be too faint to be detected at the present time, following the significant mass-loss that must have taken place to form the Quadrantid stream. Thirdly, there is at present a considerable body of opinion suggesting that some dormant comets could be mistaken for asteroids (see Williams 1997), the argument being that dust slowly chokes the vents on the nucleus and hence prevents further outgassing. There is no real consensus on the time-scale over which this might happen, but a few tens of orbits may be sufficient. It is therefore possible that the parent of the Quadrantids was an active comet, feeding meteoroids into the stream, no more than a couple of hundred years ago, but is dormant at the present epoch. It does not follow that the parent is permanently dormant – a collision with a meteoroid from the daughter stream, as was suggested by Williams et al. (1993), could reactivate the nucleus at any time. If and when this happens, the problem of finding the missing parent will, of course, be solved; the comet could have become dormant so that it now looks essentially like an asteroid. We will discuss these alternatives in turn.

2 POSSIBLE PARENTS ON ORBITS DIFFERENT FROM THAT OF THE QUADRANTIDS

As mentioned earlier, one way in which the parent of the Quadrantid stream could have become 'lost' at the present time is for the orbit of the parent to have evolved differently from the stream evolution. There are two distinct ways in which this could come about, the more obvious being that the parent experienced a very closer encounter with Jupiter. This might have produced a sudden change in the orbital parameters, making it impossible to associate the body on the new orbit, even if it could be observed, with the Quadrantid stream. The second possibility is that the orbital evolution of the parent is slightly different from that of the Quadrantid stream because the initial orbits are slightly different. These differences increase with the passage of time so that the current observed orbits are significantly different. Unlike the situation in the first case, numerical integration might be able to verify the association in this second case. We should note that in this second case, even though the changes in the orbit are slower, it is still possible that the parent can no longer be found. The perihelion distance of the orbit may have decreased through the eccentricity increasing so that the parent became a Sun-grazer.

The first suggestion of a possible parent for the Quadrantid stream was made by Hasegawa (1979) and belongs to the first of our two categories defined above. This suggested parent was Comet 1491 I, which had the following orbital elements in 1491, as deduced from the observations: $q=0.761$, $i=73\overset{\circ}{.}4$, $\Omega=279\overset{\circ}{.}5$ and $\omega=164\overset{\circ}{.}9$, the orbit being assumed parabolic. In reality, the eccentricity is undetermined rather than being unity, since the observations of 1491 did not have an arc of a sufficient length and accuracy to allow a determination to be made. Of course, the eccentricity must be greater than about 0.5, otherwise the comet would not reach an aphelion distance large enough for it to stop outgassing. As can be seen, this orbit is quite similar to that of the Quadrantids, even if we accept that its eccentricity could take any value between 0.5 and 1. We have already pointed out that the orbital evolution can potentially be rapid, and so it is more meaningful to compare the orbital elements of the comet and the Quadrantids on the same date. The mean orbit of the present Quadrantid stream has already been numerically integrated back to 1491 by Williams & Wu (1993a), who give the orbital elements on that date as $q=0.7582$, $e=0.7419$, $i=70\overset{\circ}{.}5$, $\Omega=284\overset{\circ}{.}0$, and $\omega=164\overset{\circ}{.}3$. These orbital elements are in remarkably good agreement with those given for the comet, but it would be helpful for the comparison if we could place further constraints on the eccentricity. Hasegawa (1979) and Williams & Wu (1993a) investigated the possibility that the 1491 comet had been observed at other apparitions, and a comet seen in 1385 was suggested as a good candidate. The orbital element for this 1385 comet are $q=0.79$, $i=103°$, $\Omega=288°$ and $\omega=182°$, very similar to the orbital elements of the comet of 1491, although again no value for the eccentricity could be derived from the observations. However, if these observations are of the same comet, then the time interval between their appearances, namely 106 yr, must represent an integer number of completed orbits. One solution, suggested by Williams & Wu (1993a) is that this interval represents 20 orbits, each with a 5.3-yr period. Such a period implies a semimajor axis of slightly over 3 au and an eccentricity of 0.76. In this case, the agreement with the Quadrantid orbit is remarkably good. Williams & Wu (1993a) also showed that if the actual eccentricity was 0.77, the comet would experience a close encounter with Jupiter in the middle of the 17th century, resulting in a drastic change in orbit so that the comet could not be recognized after this date as being the same comet or appear to be associated with the Quadrantids. This scenario thus falls into the category in which the orbit of the suggested parent comet may have changed dramatically since 1491. In this case, new meteoroids would certainly have been fed into the stream as late as 1491, and possibly up to the 17th or 18th century. It is unlikely that the comet could have remained on this orbit up to the 19th century, since comet detection was by then becoming much more systematic and if the comet of 1491 was still on the same orbit during this period, it would undoubtedly have been recovered again. The only additional information that can be considered in connection with the above hypothesis is the age of the Quadrantid stream. Jenniskens et al. (1997) have analysed recent observational evidence, concluding that the peak of the Quadrantid shower activity is narrower and sharper than had hitherto been thought, implying that it must have been formed from newly ejected meteoroids in the recent past, i.e., less than about 500 yr ago. Unfortunately, an acceptance of this conclusion would still not allow us to dismiss the above hypothesis, since the beginning of the 19th century must still be regarded as the very recent past within this context. The drawback with this particular suggestion for the Quadrantid parent is that, irrespective of whether it is actually correct or incorrect, there seems to be no obvious way of testing further which is the case. This is at best unsatisfactory, and the same will, by definition, be the case for any other postulated solution that requires the removal to be unpredictable locations of the ‘parent’.

The only other concrete suggestion for the Quadrantid parent made to date also belongs to the first of our categories. McIntosh (1990) has advocated that the parent is 96P/Comet Machholz (1986VIII). The current orbital elements for this comet are $q = 0.1268$, $e = 0.9580$, $i = 59\overset{\circ}{.}933$, $\omega = 14\overset{\circ}{.}528$ and $\Omega = 93\overset{\circ}{.}805$. The semimajor axis is 3.01995 au, implying an orbital period of 5.25 yr. With the exception of the semimajor axis, and thus the period, there is no obvious similarity between this orbit and that of the Quadrantids today. The basis for claiming that this comet is the parent is that the orbits were very much more similar in the past. For example, according to Jones & Jones (1993) the orbital elements of this comet 2500 yr ago were $q = 0.5689$, $e = 0.81126$, $i = 73\overset{\circ}{.}88$, $\omega = 348\overset{\circ}{.}312$ and $\Omega = 103\overset{\circ}{.}636$. The orbital evolution of the comet and that of the stream are also very similar, both showing changes with a 4000-yr period (Gonczi, Rickman & Froeschle 1992). The evolution is very similar to that shown in Figs 1 and 2 for the Quadrantid stream. These figures were obtained from our own integrations and are described later. They are also virtually identical to those found by Williams, Murray & Hughes (1979) and Wu & Williams (1992). A model meteoroid stream, generated by ejection of test particles from Comet Machholz about 7.5 millennia ago, was investigated by Babadzhanov & Obrubov (1992). On the basis of this model, they concluded that the Quadrantids and seven other recognizable meteor streams were produced by 96P/Machholz. Hence the Quadrantids may represent part of a stream complex rather than a single stream with a single parent. It should be noted that the comet of 1491 cannot be an earlier apparition of Comet 96P/Machholz since, according to the numerical integrations, the orbits in 1491 were significantly different. Of course, one could reconcile all the orbits and claim that perhaps 4000 yr ago there was a fragmentation leading to the formation of the nucleus of comet 96P/Machholz, the nucleus of the comet of 1491, and perhaps a large family of debris. Each has evolved slightly differently to form the two comets that we have been discussing, as well as the Quadrantid meteoroid stream.

As already mentioned, the evolution of orbits in the region occupied by the Quadrantids is complex and possibly chaotic. Wu & Williams (1992) identified five different groups of meteoroids amongst those identified as belonging to the Quadrantids, all evolving in a similar periodic manner, but with different periods. (This evolution is also shown in new numerical integrations later in this paper.) In terms of accepting 96P/Machholz as a parent, this raises difficulties. It requires the stream to have formed at least several thousand, if not tens of thousands of years ago, so that the orbits of 96P/Machholz and the Quadrantid meteoroids were all similar. The meteoroids then evolved at different rates so that for most of the intervening time interval they moved on orbits with very different orbital elements, coming into coincidence again at the current epoch so that we see them as Quadrantids. A very similar argument was used by Jenniskens et al. (1997) for not accepting 96P/Machholz as the primary parent of the stream. Of course, it is not a fullproof argument – in the numerical integrations the stream and comet did behave in the described fashion and so presumably the real stream and comet can behave in a similar way and, if no other simpler solution can be found, the solution becomes acceptable. However, it does suggest that we should look for other solutions.

3 THE PARENT CURRENTLY BEING AN UNDETECTED ACTIVE COMET

The second possibility suggested in Section 1 for our current inability to recognize the parent of the Quadrantid stream is that this body is currently still moving on an orbit close to the mean orbit of the Quadrantids but that the process of forming the meteoroid stream, which involves the ejection of a large amount of mass, has reduced the comet to a level at which it is no longer detectable from Earth. We can make an estimate of the probability of this being the case.

The Quadrantid shower produces a ZHR of about 100 meteors. Since meteors burn at 90–100 km height in the atmosphere, this rate corresponds to a flux per hour over an area of around 10^5 km^2, assuming a mean radiant viewing angle of about 30°. The shower lasts for about a day and, if we assume that the cross-section of the Quadrantid stream is circular, this gives it an area of about 5×10^{14} km^2 (a non-circular cross-section would give a larger area). Hence, in the portion that we see of the stream, at least 5×10^{11} meteoroids cross the ecliptic per hour. The mean orbital period is 5.3 yr, and meteoroids are crossing the ecliptic throughout this interval (although we do not see them as the Earth is not there). This requires that the Quadrantid stream contains at least 2.5×10^{16} meteors. These will, of course, be of varying mass but, if we assume, as in Williams et al. (1993), that the mass distribution index is about 2.0, then the mean mass of a meteoroid is about 0.08 g. This gives a total mass for the part of the stream that is observed as the Quadrantid shower of 2×10^{15} g. Bearing in mind the approximate nature of all the values assumed, this estimate is in excellent agreement with the estimate of 1.3×10^{15} g by Hughes & McBride (1989), or 0.47×10^{15} g by Jenniskens (1994).

In this scenario, we are discussing the possibility that the comet is still active now but remaining undetected; the dormant comet possibility is discussed in the next section. If it is active now, then the fraction of the nucleus remaining must at least equal what we currently find ejected into the stream (Hughes & McBride 1989) and, since the gas-to-dust ratio in comets is generally taken to be about 2:1, the current mass of the nucleus must be at least 6×10^{15} g so that, taking its density to be similar to that of the Halley comet, the radius of the nucleus is slightly over 1 km. Again taking the albedo to be 4 per cent, a value believed to be typical for comets, the nuclear magnitude H_0 (the magnitude the nucleus would have if it were at 1 au from both the Sun and the Earth and at zero phase angle) is about 17. Hence, if the comet were to be dormant, then for a large fraction of its orbit, it would be difficult, but by no means impossible, to detect, having a magnitude of 24 at aphelion; at its potentially closest approach to Earth, however, it could be as bright as magnitude 8.5. In this scenario, the comet is not a bare nucleus (otherwise it would be dormant) and must be outgassing. Outgassing produces a change in the dependence on heliocentric distance and on the value of H_0. A typical value for the change in H_0 is about 8 mag. Hence we would expect the Quadrantid parent to be a comet with H_0 being at least as bright as 9th magnitude when outgassing. Rather remarkably, if we take a formula given by Hughes (1990), namely

$$H_0=5.7-5\log R-2.5\log f,$$

where R is the nucleus radius in km, and f is the fraction of the surface that is active, found to be about 1/30 for Halley, then for the value of R deduced above, we also conclude that H_0 is about 9th magnitude.

According to Hughes (1990), all short-period comets with H_0 brighter than 9th magnitude have been discovered. Even if the estimate for H_0 is in error by 1–2 mag, it has to be remembered that the comet we are looking for, i.e., a comet moving on an orbit similar to that of the Quadrantids, is capable of passing very close to Earth and is of a short period (of order 5 yr). Thus it will have made about 15 apparitions since photography was common, and at least two since CCD detectors became common. It is thus exceedingly unlikely that an active comet that is moving on a similar orbit to the Quadrantids has escaped detection. This moves us on to our third possible scenario for failing to identify the parent, namely that it is now dormant and being mistaken for an asteroid.

4 A DORMANT COMET AS THE PARENT

Even the early integrations by Williams et al. (1979) showed that the semimajor axis of Quadrantid-like orbits stayed quite constant, while the inclination, eccentricity and perihelion distance showed sinusoidal variations with a period of 2000 yr or more. They also showed that the longitude of the ascending node (Ω) and the argument of perihelion (ω) both remained constant for long periods and then underwent very rapid changes of around a degree per year over an interval of 100–200 yr. Such a behaviour was confirmed by the more detailed and longer integrations by Wu & Williams (1992). We also carried out further integrations; the results of these are shown in Figs 1 and 2, and will be discussed later in this paper. Since we do not know whether or not we are presently at an epoch when rapid changes in Ω and ω are taking place, we have based our search for the dormant parent on finding objects with the correct value of the three remaining orbital elements, namely the inclination, perihelion distance and eccentricity. Since for any orbit, $q=a(1-e)$ and $P^2=a^3$, the semimajor axis, a, or the period, P, could have been used instead of either perihelion distance, q, or eccentricity, e. As a data base for our search, we used the catalogue of asteroid orbits available on the World Wide Web and generated by E. Bowell at the Lowell Observatory (ftp://ftp.lowell.edu/pub/elgb/astorb.html). In order to conduct a search, limits are required on the orbital elements within which the orbit is acceptable. In the context of the dynamics of meteor streams, it has been necessary for some time to develop quantitative methods for comparing orbits or for measuring the differences between two orbits. The first quantitative measure was by Southworth & Hawkins (1963) and was simply based on the sums of squares of the differences between each of the orbital elements. This has the obvious disadvantage that a difference of say 0.1 au in perihelion distance was given exactly the same weight, irrespective of whether the actual perihelion distance was 0.2 or 20 au. For this reason, a modified difference measurement was introduced by Drummond (1981), and is now generally known as the D' criterion. For our purposes, since we are not taking account of differences in ω and Ω, the D' criterion becomes

$$(D')^2=[(q_1-q_2)/(q_1+q_2)]^2+[(e_1-e_2)/(e_1+e_2)]^2 +[(i_1-i_2)/180]^2, \tag{4.1}$$

where q_1, e_1 and i_1 refer to the Quadrantid mean orbit, and q_2, e_2 and i_2 to the orbit being tested. The full expression when both Ω and ω are included can be found, for example, in Williams & Wu (1993b). The smaller the value of the quantity D' obtained, the more similar the two orbits are. A value of zero for D' clearly indicates a perfect match, i.e., identical orbits, while the maximum value for D', giving a 'perfect mismatch', is given when $(D')^2=3.5$ or $D'=1.87$. A value of D' less than 0.105 has been generally taken to indicate similar orbits, so that the two meteoroids are deemed to belong to the same stream (see, e.g., Drummond 1981, Wu & Williams 1992, Williams & Wu 1993b and Arter & Williams 1997). For the purposes of determining acceptable limits on each of the relevant orbital elements, we calculate in turn the range of values for q, e and i so that the maximum variation in each of these elements alone (that is assuming that the other two elements had exactly the Quadrantid value) would produce the value of D' of 0.105. In other words, we require

$$q_1-q_2<0.105(q_1+q_2),\qquad e_1-e_2<0.105(e_1+e_2),$$
$$i_1-i_2<0.105\times180^\circ, \tag{4.2}$$

the logic being that if any one of these conditions is not satisfied, then D' cannot be less than 0.105. Inserting the adopted values for the orbital elements of the Quadrantids, these limits translate to

$$0.7889 < q_2 < 1.2025, \qquad 0.5516 < e_2 < 0.8408,$$

$$52^\circ\!.50 < i_2 < 90^\circ. \qquad (4.3)$$

To our great surprise, only one asteroid out of a data base of over 8000 satisfied these conditions, namely asteroid number 5496. To check that a number of potential parents were not being excluded through failing only one of the limits by a very small amount, the limits were widened so that they corresponded to a D' value of double the original value, namely 0.21, for each of the element. This translates to the limits on our three orbital elements being

$$0.6359 < q_2 < 1.4918, \qquad 0.4446 < e_2 < 1.0000,$$

$$33^\circ\!.60 < i_2 < 90^\circ. \qquad (4.4)$$

Here the upper limits on e and i have been taken as 1 and 90° rather than the values given by calculation from the equivalent of conditions (4.2), since these are the actual upper limits for asteroidal orbits. When the search was repeated with these new wider limits, only a further 11 asteroids were found in the data base. Of these 11 asteroids, one (6909 Levison) failed all three of the initial tighter limits given in (4.3), and so this asteroid was rejected as a potential parent moving on the Quadrantid orbit. A further seven asteroids failed two of the initial limits expressed in (4.3). These are 1580 Betula, 1866 Sisyphus, 4257 Ubasti, 4596, 5131, 1992 AB and 1994 PN. Since even the initial limits are actually quite wide, these seven asteroids were also rejected as potential parents. This leaves three asteroids, 6455, 1982 YA and 1994 TW1, where two of their orbital elements satisfy the narrower limits given in (4.3), while the third element satisfies the wider limit given in (4.4). With a fairly small subset of asteroids to consider, it is easy to calculate the actual value of the Drummond D' criterion. Out of our initial set of 12 asteroids, only four had a D' value less than 0.21, i.e., twice the accepted limit. These were 1580 Betula (0.207), 6455 (0.208), 1994 PN (0.190) and 5496 (0.063). None of the first three comes anywhere near satisfying the standard condition of 0.105, while 5496 easily satisfies it. We thus have a rather surprising conclusion that there is only one asteroid, namely 5496, within all the known asteroids that has an orbit that could be claimed to be similar to the mean orbit of the Quadrantids at the present time.

It is also instructive to compute the corresponding values of D' for Comet 1471 and for 96P/Machholz with the same assumption regarding Ω and ω. The resulting values are 0.135 and 0.79. Hence, based on the orbital elements considered, the comet of 1471 is not quite as good a match to the Quadrantids as 5496, while comet Machholz is a far worse fit than the six asteroids that we have dismissed. This is not surprising, since the case for comet Machholz was based on orbital similarity several thousand years ago, a similarity that is claimed to have been lost through different orbital evolution. We also note that the match in Ω and ω is much better for the comet of 1491 than for 5496.

The remainder of this paper is concerned with a discussion of asteroid 5496 within the context of it being associated with the Quadrantid stream.

5 ASTEROID 5496 1973 NA

This asteroid was first discovered in 1973 and given the temporary designation 1973 NA. It was independently discovered again in 1992 and given the temporary designation 1992 OA. When it was recognized by the Minor Planet Center that these two sets of observations were of the same object, it was assigned the permanent number 5496. The orbital elements at epoch 1997 June 1 are $a = 2.4329351$, $e = 0.6380699$, $i = 68^\circ\!.030856$, $\omega = 118^\circ\!.244998$ and $\Omega = 101^\circ\!.079372$. The corresponding perihelion distance is $q = 0.8805524$, and the orbital period is 3.79486 yr. It has an absolute magnitude H_0 of 15.3, a very reasonable value for a dormant comet, bearing in mind that we concluded earlier than the minimum value for the nuclear magnitude of the parent comet was brighter than magnitude 17. The value of the phase-correction parameter G is 0.15. The correlation between values of G and the taxonomic type is discussed in Lagerkvist et al. (1992) and Piironen et al. (1997). Based on this, we can conclude that 5496 is a low-albedo object, probably of C type or possibly M and definitely not S or R. Although this does not prove that 5496 may be a dormant comet, the converse would probably have indicated that it was not – a dormant comet is very unlikely to be mistaken for an S-type asteroid.

Based on the above discussion, we believe that a strong case can be made for an association of 5496 and the Quadrantid stream. However, we should note that there are significant differences between the values of the two orbital elements Ω and ω for the Quadrantids and 5496. These were the two orbital elements that are capable of very rapid changes. Hence the differences now may simply indicate that in the recent past either the orbit of the Quadrantids, or more likely, the orbit of 5496 has undergone such a rapid change. The other element, requiring a much longer time-scale to change significantly, remain in close agreement. To determine whether or not this is the case requires an investigation of the orbital evolution of 5496 and a comparison of this with the orbital evolution of the Quadrantid stream.

6 ORBITAL EVOLUTION

The orbital evolution of the Quadrantid meteoroid stream has been investigated by many authors, many of whom have already been cited. The evolution of the orbits of 118 actual Quadrantid meteoroids were integrated by Wu & Williams (1992) over a time interval of 6000 yr. This investigation identified five sets of meteoroids that behaved similarly. Three sets, called Set I, Set II and Set III, showed clear periodic variations in their orbital elements, the only difference between them being the time-scale over which the periodic changes occurred. The fourth set, consisting of 29 meteoroids, showed virtually no change in any of the orbital elements over the interval of the integration. All of these meteoroids were on a more eccentric and longer period orbit that did not make any close approaches to Jupiter. Whether or not these meteoroids actually belong to the Quadrantids can be debated elsewhere; what is clear is that their behaviour is not typical of the Quadrantids. The fifth set, consisting of 15 meteoroids, demonstrated all the characteristics of chaotic motion, even on a short time-scale.

Wu & Williams integrated the mean orbits of each of these sets over a much longer time interval of 30000 yr. These data provide a good base with which to compare the orbital evolution of potential parents. We have integrated the orbit of asteroid 5496 over a similar time interval by using the Runge–Kutta–Nystrom technique, with the coefficients as determined by Dormand, El-Mikkawy & Prince (1987). The gravitational fields of all the planets other than Pluto were included. The increase in computer time required to integrate the orbits of a few additional massless bodies over and above the asteroid of interest is fairly minimal. Hence it was decided also to include the integration of an object on the mean orbit of each of the three sets integrated by Wu & Williams. We have integrated these systems both forwards and backwards in time, whereas Wu & Williams integrated only backwards. This procedure has a number of advantages. First, a comparison of the two integrations allows a mutual test for the correctness of both. Secondly, by the procedure, the actual interval over which the orbits of the three Quadrantid sets of meteoroids have been integrated is increased to 60000 yr. Thirdly, and most important for this investigation, the motion of asteroid 5496 has been integrated within exactly the same environment and with exactly the same techniques as the Quadrantid meteoroid sets with which the evolution is to be compared.

The results of these numerical integrations are shown in Figs 1 and 2. Fig. 1(a), (b) and (c) are the mean orbits of Sets I, II and III, respectively, of real Quadrantid meteors as defined by Wu & Williams (1992), while Fig. 1(d) shows the orbital evolution of asteroid 5496 back in time for 30000 yr. The corresponding diagrams in Fig. 2 are forward in time. The results shown in Fig. 1(a)–(c) are indistinguishable in all major characteristics from those given by Wu & Williams. This confirms the general picture of the evolution of the meteoroids described by Wu & Williams, in particular the periodic behaviour with the period being about 4000 yr (for one cycle) in Set I, 6000 yr in Set II and 10000 in Set III. This confirmation is important, since there were two minor differences in the models integrated. In this integration, all the planets except Pluto were included, whereas Wu & Williams also excluded Mercury, Venus and Mars. However, Wu & Williams included solar radiation pressure, while we have not. The similarity of the two sets of results therefore shows that none of these effects are important in affecting the general behaviour of the Quadrantids. In Fig. 2, the same general pattern is clearly seen so that, as expected, the periodic behaviour continues into the future. However, there is a very small secular increase in eccentricity that can be seen running through both the backward and forward integration. It is easier to detect because of the double time interval, but is also present in the Wu & Williams results. This increase in eccentricity causes the perihelion distance to decrease so that collision with the Sun becomes possible. The integration was terminated when this occurred and can be seen in Fig. 2 where the evolution curve terminates. The longitudes of the ascending node, for all three sets of meteoroids, have values of around 280° (the current value for the Quadrantids) and about 100° (the current value of the orbit of 5496) for roughly equal time intervals. We also note that the switch from one value to the other is extremely rapid when it occurs.

Turning to the orbital evolution of 5496, from Figs 1(d) and 2(d) we see that the evolution of four of the orbital elements, q, e, i and Ω, is qualitatively very similar to the evolution of the same elements within the Quadrantid meteoroids, although the period of the variations for asteroid 5496, at about 15 000 yr, is slightly longer than for any of the three sets. The small secular increase in eccentricity is not evident, this orbit appearing to be particularly stable. The fifth orbital element, the argument of perihelion, ω, has a different behaviour for 5496 compared to its behaviour in all three of the Quadrantid sets, librating between roughly 60° and 120° in 5496, while circulating in all the Quadrantids. This again illustrates the stable nature of the published orbit for this asteroid. To investigate whether or not the behaviour we are describing is a peculiarity of the particular orbital elements selected for 5496, we also integrated a further 30 orbits where the orbital elements were changed by up to 0.1 per cent in each of the elements a, e, ω and mean anomaly at the present time. No significant differences were found between the evolution of these orbits and that shown for 5496 and, for the sake of brevity, the results of these integrations are not shown.

The numerical integrations show that there is a strong similarity between the orbital evolution of the Quadrantids and of asteroid 5496. This by itself proves nothing, of course, since they are all orbiting within the same locality of the Solar system and are thus subject to broadly similar perturbations. The differences in the length of the period of the variations between the four cases investigated shows again that this is a locality where, because of close encounters with Jupiter and possible mean motion resonances, the details of the evolution are closely governed by the exact location, slightly different orbits can evolve on very different time-scales, although the general changes are similar and periodic. As far as a discussion of the similarity of orbits is concerned, this means that, at a particular epoch, all the orbits of concern can be very similar, but as time passes, the changes get out of phase so that the orbits are dissimilar, only to coincide in phase again, given sufficient time. However, the time for all sets to coincide in phase again with periodicities of 4000, 6000, 10000 and 15000 yr is 60000 yr.

The last time-scale is almost meaningless for two reasons. First, we are not looking for the interval from being in phase to being in phase again, since the Quadrantids and asteroid 5496 are currently out of phase. Secondly, it is certainly incorrect to believe that all the Quadrantid meteors that we currently observe originated at the same time. The formation of all major streams must have taken place over many perihelion passages of the parent comet. About 2000 yr ago the orbital elements of Set I would have been very similar to those of 5496, while 300 yr ago both Sets I and II would have been on orbits similar to that of the asteroid. We have to be careful with such numerics, however – both the orbit for Set I and that for Set II, and indeed all the other sets, are mean orbits obtained for a family of meteoroids that evolve similarly. Looking at individual orbits from other integrations, test particle 7 from Williams et al. (1979), for example, had a value for the longitude of the ascending node equal to that of 5496 about 100 yr ago, while the real meteoroid 2033 of Wu & Williams (1992) also evolved from an orbit similar to that of 5496 less than 1000 yr ago. We should therefore take an interval of 1000 yr or so only as an indication of the time-scale in the past when the orbits of the Quadrantids were similar to that of asteroid 5496.

7 CONCLUSIONS

In this paper we have discussed various possibilities regarding the identification of a possible parent for the Quadrantid meteoroid stream. Although the evolution of Comet 96P/Machholz is very similar to that of the mean Quadrantid orbit, the fact that the two were not in coincident for the last several thousand years suggests that this is not the body responsible for the strong narrow peak in the Quadrantids, which, according to Jenniskens et al. (1997), is considerably younger than this. However, if one believes, as suggested by Babadzhanov & Obrubov (1992), that the Quadrantid stream is part of a much larger complex of meteor streams (they suggest that the Ursids, Carinids, Velids, Delta Aquarids, Arientids and Alpha Cetids may all be part of this complex), then Comet 96P/Machholz almost certainly played a part in feeding meteoroids into this complex. In this picture, a single parent split at some unidentified time in the past into at least two significant fragments, one fragment 96P/Machholz feeding the complex, including the older parts of the Quadrantid stream, and another frament which evolved with the Quadrantids and continued to feed meteoroids into the stream until the very recent past. The latter fragment could have been observed as the comet of 1491, although the uncertainty in the orbital element of this comet does not allow us to use numerical integration to prove that this is the case. However, if the eccentricity of this orbit was below 0.85, then the long-term orbital evolution is similar to that of the Quadrantids, 96P/Machholz and 5496 (Wu 1992), the period of the variations being about 4000 yr when $e=0.75$. Williams & Wu (1993a) also demonstrated that, for this range of eccentricities, the comet would be ejected on to a much larger orbit through a close interaction with Jupiter on a short time-scale after 1491, with the large change occurring in the 17th century if the eccentricity has been 0.77. Thus the comet of 1491 does appear to be a reasonable candidate for feeding into the Quadrantid stream some of the younger meteoroids.

The main question that this paper addressed was whether or not another, possibly now-dormant, fragment could also exist. Further, if such an object was identified, we asked whether or not it was still necessary to have a fragmentation of the nucleus, or whether this body alone could explain the Quadrantids. 96P/Machholz and the comet of 1491 would then simply be coincidentally on similar orbits in an area of the Solar system where orbital evolution is rapid and where it is thus much easier to find a similarity in orbits at a given time through coincidence.

We argue that the strong similarity between the values of the orbital elements of asteroid 5496 and of the Quadrantid meteoroid stream is a strong indicator of some connection. Further support for this viewpoint comes from the general similarity in the orbital evolution and the general physical characteristics of the asteroid. In conclusion, we therefore offer the following scenario. At some unspecified time in the past, but at least several thousand years ago, possibly at one of the epochs when the perihelion distance was quite small, the nucleus of the comet split into several fragments. Such splitting could have been a 'one-off' event, but is far more likely to have been a series of events. Three remnants of this process can be identified, namely the comet of 1491, Comet 96P/Machholz and asteroid 5496. Meteoroids were probably ejected throughout the interval from each of these three fragments, and possibly from other unidentified fragments. Some of the observed Quadrantid meteoroids on this picture could be very young, ejected from these unidentified fragments or from the nucleus of the comet of 1491. Finally, the fate of other parts of the original comet is not known, and a further fragment or fragments of the original body may still be moving in the Solar system, waiting to be identified or located.

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