THE DISCOVERY AND ORBIT OF (2060) CHIRON

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"Slow-moving Object Kowal" was recognized by the first author on 1977 November 1 on plates obtained with the 122-cm Schmidt telescope at Palomar two weeks earlier (Kowal 1977a). The object, asteroidal in appearance and of photographic magnitude about 18, was found to have moved less than 3' between similar 75-minute exposures made on October 18 and 19. For something only 8° from opposition this retrograde motion was significantly slower than the 8'-15' daily motion of normal minor planets at opposition and immediately suggested that the object was located at almost the distance of Uranus. There was a slight possibility that the object was closer and moving almost directly toward or away from the earth, but the fact that the two trails were identical in length to ± 6 percent suggested that this was unlikely. That the object was well beyond the main belt of minor planets was confirmed when Gehrels (1977) succeeded in identifying it close to the extrapolated position near the corner of an exposure obtained with the same telescope on October 11.

From accurate measurements of the Gehrels plates of October 11 and 12, the discovery plates of October 18 and 19, and further plates obtained with the 122-cm Schmidt on November 3 and 4, the third author could demonstrate conclusively that the object was located between 14 and 17 AU from the earth (Marsden 1977a). The orbit itself was completely indeterminate, however, with the various combinations of three observations departing from great-circle motion by less than 3", and a low-inclination near-circular orbit of semimajor axis $a \simeq 16$ AU was selected as a compromise between a set of ellipses with rapidly increasing aphelion distances Q and slowly diminishing perihelion distances q (to 12.6 AU in the case of a parabola), and the complementary set with q rapidly decreasing to a limiting value of around 7 AU for an orbital eccentricity $e \simeq 0.5$.

With the availability of a pair of observations on November 9 and 10 it became clear that the more eccentric orbits of the large-Q set (e > 0.4, say) were no longer viable, and when further observations, extending to November 18, became available, it was apparent that only the small-q orbits could be considered. By this time it was in fact possible

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to make a meaningful least-squares solution for all six orbital elements. The result from the 15 available observations gave $e = 0.35 \pm 0.04$, $q = 9.9 \pm 1.2$ AU. It seemed strange that the object, by then designated 1977 UB, had been discovered so far from perihelion, when it should have been significantly brighter. There was also the point that the object might be strongly perturbed near perihelion by Saturn, although the revolution period $P = 59.1$ years suggested that the orbit's stability could perhaps be maintained by a 1:2 resonance with Saturn.

Still, this orbit clearly indicated that 1977 UB would have been off the edge of the 1975 discovery plates of the presumed fourteenth satellite of Jupiter, excellent plates that were repeatedly examined in vain for this object. The first author had taken other plates in the general vicinity of 1977 UB on pairs of nights in July 1972, October 1970 and September 1969, however, and the new orbit suggested that there was an excellent chance the object would be on the 1969 plates. After a brief search it could be identified (Kowal 1977b) only about 55' east and 41' north of the predicted position, and an orbit fitted to the 17 observations (Marsden 1977b) showed quite definitely that $e = 0.38$, $q = 8.5$ AU (and hence $Q = 18.9$ AU, $a = 13.7$ AU, $P = 50.7$ years). A numerical integration of the orbit within ± 550 years of the present time yielded a mean value of $P \simeq 49.0$ years, suggesting that the object was in 3:5 resonance, rather than 1:2 resonance, with Saturn. Very close approaches to Uranus would be precluded by the fact that conjunction would occur when Uranus was near its aphelion distance of 20.1 AU. It was still somewhat curious that 1977 UB had not been discovered at magnitude ~ 15 near perihelion, but perihelion passage had occurred in 1945, when few minor-planet patrols were being made, and those that were would probably have missed a very slow-moving object. The Lowell Observatory's survey for distant planets (Tombaugh 1961) would not have gone down faint enough in the 1930s and did not cover the right region of the sky in the 1940s.

After the 1969 identification had been made, additional past images of the object were uncovered in quick succession, including some on exposures in November and December 1976 with the 155-cm reflector at Harvard Observatory's Agassiz Station. Because of the small field, the chance that the object would have been recorded on plates taken with a large reflector was minute, but the field had been effectively widened with multiple exposures to follow up two minor planets discovered with this telescope some weeks earlier. A search of the Palomar Sky Survey yielded tentative images, of blue magnitude 17, on both the blue and red exposures of the appropriate field, photographed in August 1952; these images were situated about ¼° west of the predicted position in a very crowded area near the galactic plane in northwestern Sagittarius, but comparison with other Palomar-Schmidt exposures of the same region yielded no other moving objects within ½° of the prediction (Kowal 1977c). Armed with this knowledge, the second author, who was at the time inspecting a 3-hour exposure obtained in January 1941 with the 61-cm Bruce astrograph at what was then Harvard Observatory's Boyden Station (now the Boyden Observatory), directed his attention some ½° west of the predicted position and immediately noticed the trail of the object, estimated at perhaps magnitude 15 (Liller 1977). Curiously enough, this trail had been marked, but apparently never followed up, when the plate was examined in 1951 for faint galaxies. The 1941 observation clearly confirmed the 1952 identification and made it a simple matter to locate the object on similar, but inferior, Boyden plates taken in 1943 and 1948. Subsequently, images were identified on a plate taken at the Turku Observatory in 1945 (Niemi 1978) and on exposures with the Tokyo Observatory's 105-cm Schmidt telescope in 1976 (Kosai 1977).

With the help of an orbit refined to fit the 1941 and 1952 observations, it became possible to identify the object on a 60-minute exposure obtained with the Bruce astrograph near the time of the object's previous perihelion passage in 1895 (Liller and Chaisson 1977), when the instrument was being tested in Cambridge prior to its removal to the southern hemisphere. By modern standards none of these ancient plates is of particularly good quality, and this trail was so weak that it seems very unlikely that any other observations of this vintage will be found.

Using an orbit determined from observations in 1895, 1941, 1952, 1969, 1976 and 1977 (Marsden 1977c), the third author has attempted to trace the motion of 1977 UB over an extended interval of time. Perturbations by the five outer planets were considered, and some of the results are shown in Figure 1. As expected, there are several moderately close approaches to Saturn and Uranus, but there was no sign of instability in the whole 5500-year span of the orbit integration into the future. During this interval 1977 UB makes only one approach within 1 AU of Saturn, to 0.86 AU in the year 4689; the only approaches within 1.5 AU of Uranus occur in 4199 (1.10 AU) and 4871 (1.14 AU), and the only approaches within 3.0 AU of Jupiter occur in 5444 (2.86 AU) and 5932 (2.96 AU). The past motion seems to have been quite stable back to an approach within 0.7 AU of Saturn in the year -1400. The earlier motion must be considered rather uncertain, but our calculation suggests that there was an even closer approach in the year -1664, possibly to within a distance of 0.1 AU. It is of course completely meaningless to attempt to trace the motion before that time.

Figure 1 indicates that during the relatively unperturbed interval the value of a seems to vary with a period averaging about 600 years; a larger fluctuation has a period of perhaps 4000-5000 years. There is perhaps some kind of temporary libration around the 3:5 resonance with Saturn, but the long-term fluctuation tends to bring the motion more under the influence of the stronger 2:3 resonance ($P \simeq 44$ years) after about the year 6000. The oscillations in e to some extent match those in a and indicate that the changes in q must be rather small. In fact, since -1664 q varies only between 8.3 and 8.7 AU. The inclination i to the ecliptic shows a rather steady increase over the range discussed, this increase evidently being correlated with the argument of perihelion ω, which advanced by about 100° from 307° to 402°(=42°), while the longitude of the ascending node Ω shows a corresponding retrogression from 256° to 156°.

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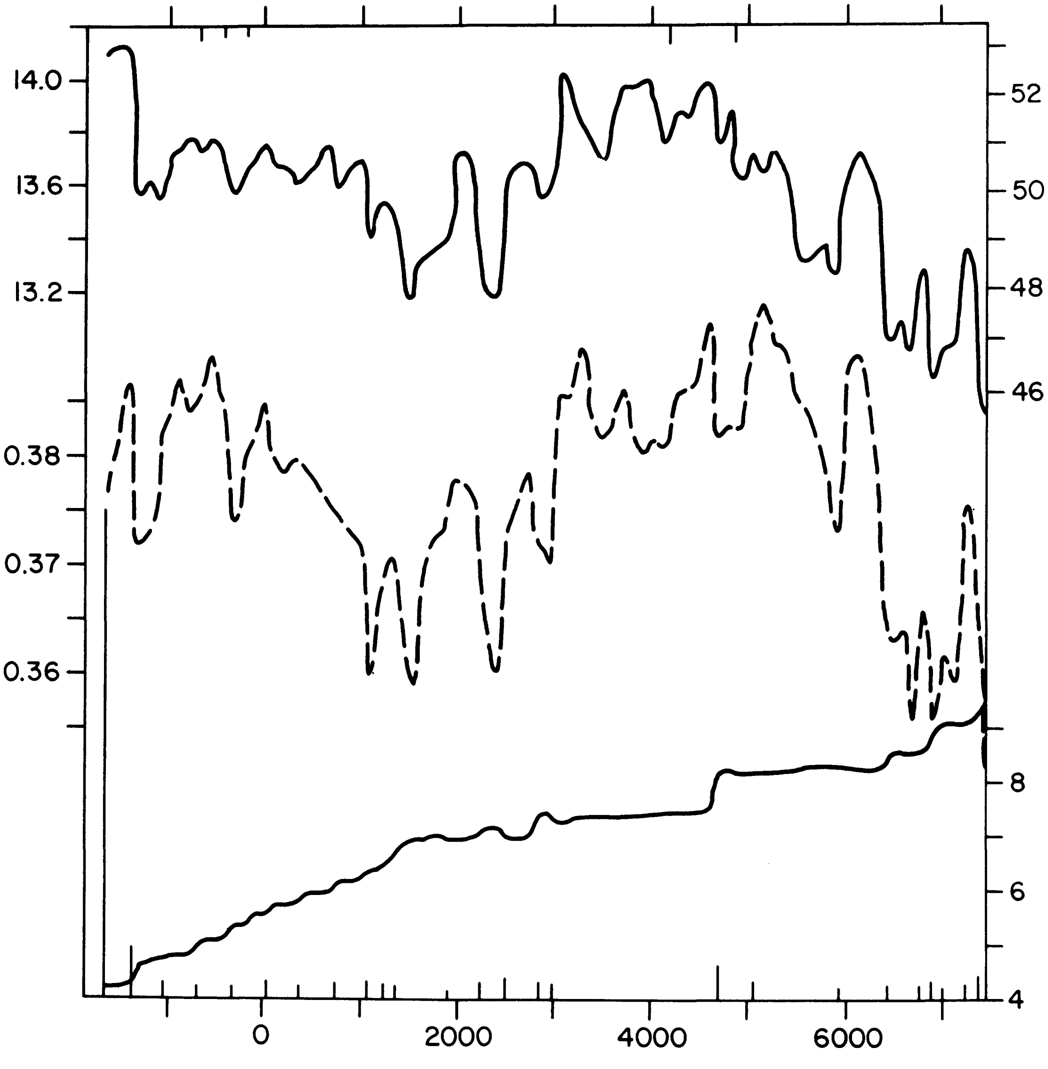

Figure 1. The variations in the orbital elements a (and P), e and i between the encounter with Saturn in -1664 and about the year 7400. The vertical lines inside the frame of the figure represent close approaches to Saturn (bottom) and Uranus (top). Only approaches Δ within 2 AU are marked, the lengths of the lines being proportional to $\Delta^{-1} - 0.5$.

The nature of 1977 UB can be only a matter of speculation. Its absolute magnitude of about 6 is comparable to the values for the brightest minor planets, but its albedo is unknown. The relatively unstable nature of its orbit, the known existence of comets at great distances from the sun and the distinct possibility that Saturn (perhaps with the help of the other outer planets) could perturb a comet with a low-inclination orbit of much longer period into one with an orbit like that of 1977 UB can of course be used as arguments for the object's cometary nature. On the other hand, 1977 UB would have to be a comet of record large size; no other comet has ever been observed beyond a heliocentric distance of 11.3 AU, and while one might guess that comet 1729, observable with the naked eye in spite of its perihelion distance of 4.05 AU, could also have had a nuclear magnitude of about 6, there is no real proof that this was the case. Even at perihelion, a cometary 1977 UB with a water-ice nuclear surface would be completely inactive. Although much smaller in size, (944) Hidalgo has also been regarded by some as an inactive comet, but with the important difference that its inactivity would be due to its water-ice content being sublimated away during its passages through perihelion: if (944) Hidalgo is a "dead" comet nucleus, 1977 UB is one that has never had a chance to live. In this connection it is useful to mention that attempts to trace back the orbit of P/Schwassmann-Wachmann 1, a large comet whose heliocentric distance currently varies between about 5 and 7 AU, lead to the result that a few thousand years ago this object, moving under the influence of both Jupiter and Saturn, had an orbit with q comparable to that of 1977 UB (although a was more like 10 AU than 13 AU).

On the other hand, both 1977 UB and (944) Hidalgo could perhaps have been perfectly ordinary minor planets, deflected into their present orbits by collisions with other minor planets and then a complex series of encounters with Jupiter (and also Saturn in the case of 1977 UB). The collisions presumably would have taken place rather recently. It can be argued that 1977 UB would be an exceptionally large collisional fragment, but it is no larger than (2) Pallas, whose highly inclined orbit also quite plausibly arose as a result of collisions.

On the whole, it seems prudent to continue to classify 1977 UB as a minor planet, and it has very recently received the permanent number (2060). The discoverer intends to give this object the name Chiron. Chiron was one of the centaurs, and it is suggested that the names of other centaurs be reserved for other objects of this same type that may be discovered in the future.

We also remark that our calculations suggest that (2060) may have approached Saturn in -1664 to about the distance of Phoebe. Chiron and Phoebe are probably of comparable size. It is therefore tempting to speculate that Phoebe and Chiron were originally members of a distinct group of related objects.

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DISCUSSION

Delsemme: Before the discovery of Chiron, I had predicted (A.H. Delsemme,1973,Astron.Astrophys.29,377) the existence of between 30,000 and 300,000 comets of intermediate period, in the same range of a and q as Chiron. If we use the observed brightness distribution of the 600-odd comets observed so far, normalized for an absolute magnitude of +4, to a radius of 4 km, 50 to 500 objects must have a radius larger than 100 km between Jupiter and Uranus and therefore the presence of a large object like Chiron is not surprising in the general population of comets that is likely to exist at these distances.

Marsden: It is also my personal opinion that Chiron is most likely to be a comet, but I don't think we should completely exclude other possibilities.

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