1998 WW31, a very eccentric binary system in the Kuiper belt.

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It wasn't until recently that the first binary asteroid was unambiguously discovered[1,2], followed by several binary near earth[3-5], main belt[6,7], and Trojan[8] asteroids. The Kuiper belt, the region of space extending from Neptune at 30 AU to well over 100 AU believed to be the source for short-period comets[9], has become a fascinating new window onto the formation of our solar system since the first Kuiper Belt object (KBO) was discovered in 1992[10]. There has been keen interest in finding binary KBOs, since the orbital parameters can provide measures of masses, and mutual eclipses could allow us to determine individual sizes and bulk densities. Here we report our discovery that the KBO 1998 WW31 is binary. Observations from the ground and the Hubble Space Telescope unveil a binary system with a highly eccentric orbit (e ~ 0.8) and a long period (~570 days), very different from Pluto/Charon, the only previously known binary in the Kuiper belt. Assuming a density in the 1 to 2 g/cm^3 range, their albedo is 0.05 to 0.08, close to the value generally accepted for KBOs, 0.04.

1998 WW31 was discovered at the Kitt Peak National Observatory 4-m telescope in November 1998 by R. Millis and his collaborators and reported [11] as a single KBO. There were only a few positions on a 42-day long arc following the discovery, and no recovery observations were made during the next opposition. Recovery is a very important step in the study of KBOs: based on positions on only a short arc, the orbit of a KBO is not well constrained and the possibility of losing it after a few years without new observations is very high. The uncertain orbital parameters of lost KBOs make them useless for subsequent analysis of the Kuiper Belt. Therefore, 1998 WW31 was included in the list of objects to be observed during a KBO photometry and recovery program by C. Veillet and A. Doressoundiram scheduled in late December 2000 on the Canada France Hawaii 3.6-m telescope (CFHT). A first image of the field of 1998 WW31 was taken on 21 December 2000, and two additional images were obtained the following night. A first look at the images right after the observations didn't reveal the presence of 1998 WW31. It is only in April 2001 that the object was recovered, when all the images of the run were re-processed in a more systematic way by C. Veillet. Figure 1 shows a composite of the recovery images.

A first analysis of these three images did not show any significant relative motion of the two components. It was unclear from these few images if 1998 WW31 was a true binary object, or if it only appeared this way by chance superposition of two non-related KBOs in different orbits but seen close to each other with apparent motions close enough to be indistinguishable over the course of two nights. In April 2001, the solar elongation angle of 1998 WW31 was too small to allow any observation. Fortunately, we had at our disposal data taken during the previous year, allowing us to look at

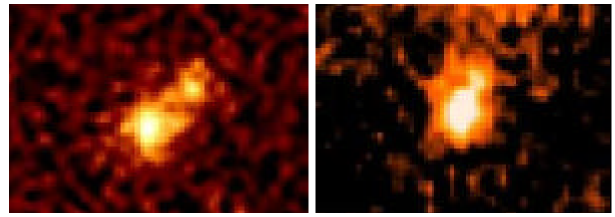

Figure 1 1998 WW31 on 2000 Dec. 22 (binarity discovery image) on the left, and nearly a year earlier on 2000 Jan. 7 on the right. The two images are a composite of 3 and 4 raw images, respectively, taken with CFH12K, the wide field imaging camera mounted at the prime focus of the Canada-France-Hawaii 3.6-m telescope. 1998 WW31 is clearly a double KBO, although the details of the orbit cannot be determined from these two images alone. The angular separation between the two sources is 1.2" in December 2000 and 0.8" in January 2000.

the object farther in the past to determine the reality of the binary. In searching the CFHT archives we found seven images of 1998 WW31 taken on 6 and 7 January 2000 by J J Kavelaars and A. Morbidelli. We generated a new ephemeris for 1998 WW31 including our new observations, and computed the KBO's position for the dates on which these images were taken. Thus, we were able to find 1998 WW31 on those images, embedded in the halo of a very bright star on the first night and close to another star on the second night, explaining why the other team was not successful in locating the object. In many of these images, 1998 WW31 was clearly elongated or even resolved into two components, The orientation and the separation of the components were different from those seen in our observations nearly a year later (Figure 1), confirming that 1998 WW31 is a binary KBO.

A further search through the CFHT observing log showed that another set of observations had been taken shortly after our December run at CFHT by H. Aussel for D. Tholen. In the MPEC where our recovery had been published [12], two observations by M. Buie at KPNO were also reported from November 2000. Subsequently, J. Parker found 1998 WW31 on images he had taken on 29 and 30 November 2000 at KPNO, and his examination of these images further confirmed the presence of both components.

We contacted all the observers who had images of 1998 WW31. The ground-based observations since the 1998 WW31 discovery that had adequate seeing to resolve the components covered slightly more than two years in six main epochs. The data are of variable quality. Some of them were acquired under conditions of poor atmospheric seeing. Due to the spacing of the observations, it was difficult to assess confidently the orbital period, though a long one (around 500 days)

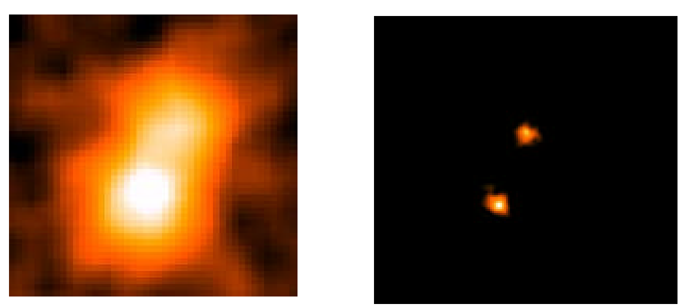

Figure 2 1998 WW31 seen from the ground at CFHT (left) on 2001 September 12.5 with an excellent seeing of 0.5", and from space with HST (right) on September 9.7. The images are at the same scale. Separation of the components is 0.59".

was more likely than a short one (150 days). To resolve this uncertainty, we obtained Director's Discretionary Time with the Hubble Space Telescope (HST) to observe 1998 WW31 with the Wide Field Planetary Camera 2 (WFPC2) instrument [13] once a month for three months. The first observations were scheduled at the earliest possible date, early July 2001, when the solar elongation angle of 1998 WW31 was larger than the HST solar avoidance angle. For each of our observations 1998 WW31 was centered on the planetary camera CCD, giving a resolution of 0.046 arc seconds per pixel.

With a separation on the sky of ~0.7 arc-seconds the two components were easily resolved (Figure 2). Observations were obtained at three separate epochs: 12 July, 9 August, and 10 September 2001. At each epoch 2 exposures were made through each of the F555W, F675W and F814W filters (comparable to the Johnson system V, R, and I filters). Data were reduced using the standard WFPC2 pipeline [25]. We performed astrometric and photometric measurements with the IRAF software. In parallel with the HST observations, we obtained ground-based observations from CFHT using the queued service observing mode operating the wide field imager. With these coordinated observations, we were able to get a well-sampled series of images over three months (with usually excellent seeing conditions at CFHT). From all these positions, the orbit of the secondary component was determined using various weight combinations in a very inhomogeneous data set. The eccentricity was found to be at least 0.5 and not well constrained on the upper side due to the lack of positions close to the pericenter. Even an orbit with an eccentricity as high as 0.9 could reasonably well fit the observations.

Since a moderate eccentricity of around 0.6 would place the date of the pericenter in early 2002, additional HST visits were obtained on Director's Discretionary Time on 30 December 2001 and 19 January 2002 to refine the ellipticity of the orbit. An additional set of HST observations made on 13 December 2001, obtained as part of a separate program were graciously made available to us by K. Noll, the PI of that program. These observations, made through filters identical to those used in our observations did however place the image of 1998 WW31 on the wide field 3 camera, and hence were of resolution half that of our other HST observations.

Figure 3 shows our best fits to the observations. The orbit computation algorithms developed for WW31 were first checked and confirmed with the pair Pluto/Charon, using the HST observations published by Tholen and Buie [14]. The same algorithms were then applied to the 1998 WW31 pair. The uncertainties assigned to the observations and used for determining the formal uncertainty on the orbital elements, are outlined on Figure 3. Two sets of orbital elements

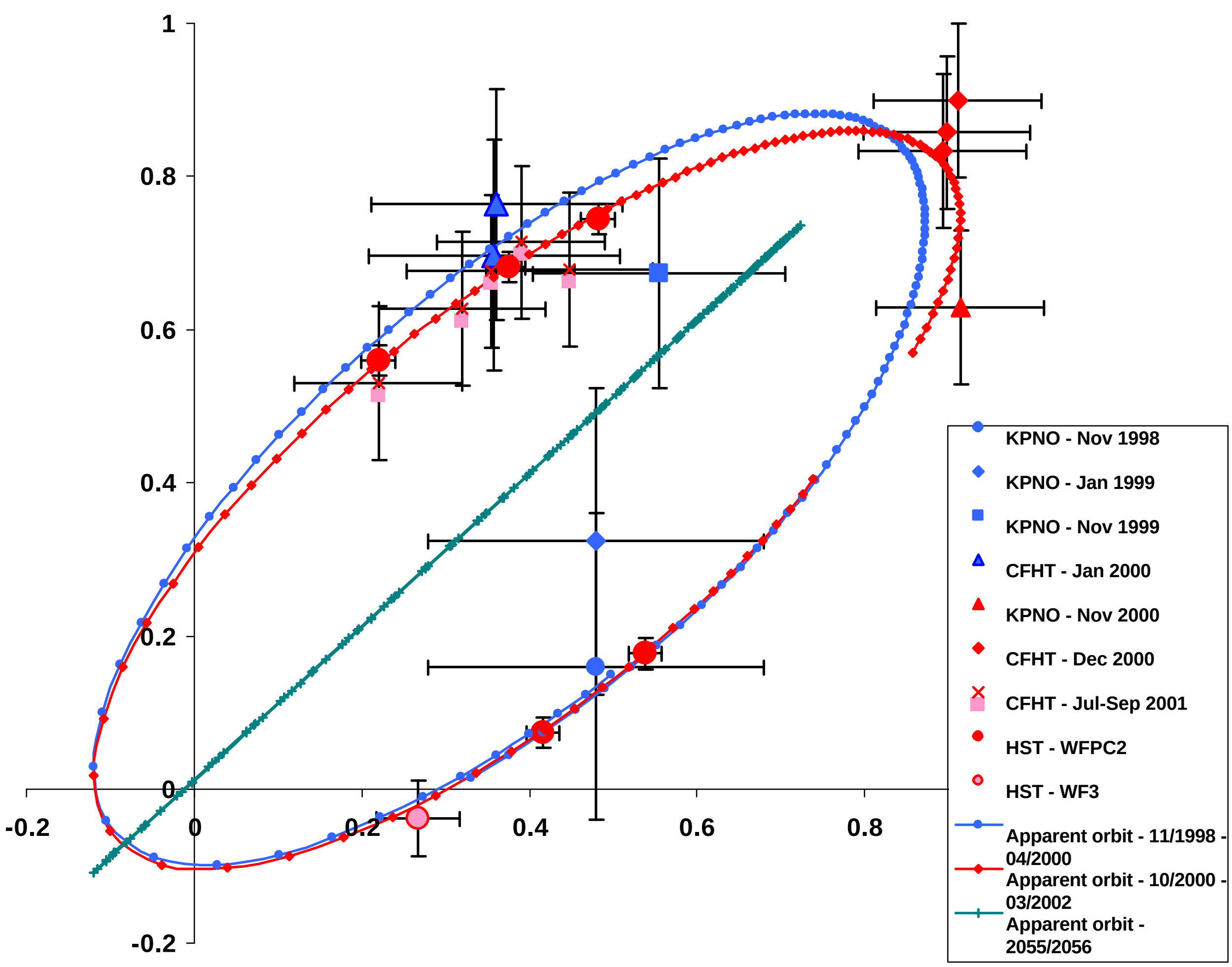

Figure 3 1998 WW31 observations, from the ground and from HST. Coordinates are seconds of arc. North is up and East is to the right. The apparent orbits at the time of the observations are shown with one dot every 5 days. The apparent obit in 2055/2056 is also plotted to show that mutual eclipses could happen at some point in nearly 50 years from now (with a few years uncertainty). The following uncertainties were assigned on the relative apparent rectangular coordinates of the faint component relative to the main one (in arc-seconds): 0.02 for the HST WFPC2 observations, 0.05 for the WF3 observation (pair poorly resolved), 0.1 for the data close to the apocenter, 0.2 for the two earliest ground based observations, and 0.15 for all the others.

	All observations	*HST only*	Charon
Period (days)	574.0 [10]	*521 [133]*	6.3872
Semi-major axis (km)	22300 [800]	*21200 [2400]*	19366
Eccentricity	0.817 [0.05]	*0.80 [0.1]*	0.0076
Inclination (degrees)	41.7 [7]	*43.8 [10]*	96.16
Node longitude	94.3 [8]	*94.6 [10]*	223.0
Pericenter longitude	253.8 [7]	*251.8 [9]*	
Mean longitude at epoch	43.4 [4]	*48.7 [16]*	
Epoch (Julian Date)	2452300.5	*2452300.5*	
R magnitudes	Pair: 23.6 (A): 24.2 (B): 24.6		
Same albedo	Diameter ratio: 1.2 - Mass ratio: 1.74		
Same density 2.0 g/cm^3 (similar to Pluto)	Diameters (A-B):118 km - 98 km Albedo: 0.087 [0.007]		
Same density 1.5 g/cm^3	Diameters (A-B): 129 km - 108 km Albedo: 0.071 [0.006]		
Same density 1.0 g/cm^3	Diameters (A-B): 148 km - 123 km Albedo: 0.054 [0.005]		

Table 1 The orbital elements (mean equator and equinox of J2000.0) of the secondary component, B, of the 1998 WW31 system with respect to its primary, A, (formal uncertainties in brackets based on the uncertainties assigned to the individual measurements used as outlined in Figure 3) and the physical properties of the 1998 WW31 components derived from the mass of the system as determined from the orbital parameters (period and semi-major axis), for various assumptions on their density. The orbital elements based only on HST data are shown to stress the importance of the ground observations in spite of their poorer quality. Charon's elements are by Tholen and Buie [14].

were computed: the first one uses only the HST observations, while the second one uses the whole set of observations. Results are given in Table 1. The HST observations, which cover one third of the orbital period, comprise two short arcs (60 and 40 days long, respectively) separated by 100 days with the pericenter occurring between them. The eccentricity is therefore well determined, but other elements, especially the period and the overall orbital geometry, are dramatically improved when all data are used, in spite of the lower quality of the early observations.

The 1998 WW31 pair is indeed very different from the Pluto/Charon system, as seen on Table 1. The most unusual feature of the orbit is its eccentricity, the largest one ever found in a binary asteroid. Additional HST observations will allow us to follow the faint component as it goes through the apocenter and to better determine the period and semi-major axis; however even the values presented in this paper are accurate enough to lead to a good estimate of the mass of the system, a first in the Kuiper belt.

The orbit is not determined well enough to predict with precision when mutual eclipses could happen. With the present solution, eclipses could take place in 2055/2056. The HST observations scheduled for the next opposition will allow a better prediction of when mutual events will occur.

Using both ground based and HST observations, the two components are found to have a magnitude difference in R of 0.4 and a total magnitude of 23.6. If we assume that they have the same albedo, their diameter ratio is 1.2. If they have the same density, it is possible to get the mass of each component. The diameters can be estimated assuming a given density. An albedo can then be derived from the observed magnitude and the estimated diameter. Table 1 summarizes the results obtained assuming various densities from 1 to 2 gm cm^{-3} (Pluto's density is about 2 gm cm^{-3}). The associated albedo values are in the range 0.05 to 0.08. The albedo of cometary nuclei, 0.04 [15], is the value generally assumed and used for KBO size estimation; however, if we use that low albedo value for 1998 WW31, then the KBO would have a very low density of roughly 1 gm cm^{-3}, considerably less than the density of Pluto.

The announcement of the binarity of 1998 WW31 was the first of what has become a series of binary KBO discoveries. Within less than a year after our announcement of the binarity of 1998 WW31, five other KBOs have been discovered to be binaries: 2001 QT297 [16] and 2001 QW322 [17] using ground-based observations, and 1996 TC36 [18], (26308) 1998 SM165 [19], and 1997 CQ29 [20] using HST. We now know of seven binary systems in a sample of nearly 600 objects. Though we have to be careful when dealing with small numbers, binarity is definitely not uncommon in the Kuiper Belt, comprising at least 1% of the currently known KBO population. ☐

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