Asteroid 433 Eros: The Target Body of the NEAR Mission

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ABSTRACT
Asteroid 433 Eros was the first near-Earth asteroid to be discovered and nearly 100 years of ground-based observations have allowed a rough physical characterization of the body. Eros is a S-type asteroid whose dimensions are approximately 40.5x 14.5 x 14.1 km. Its rotation is in a direct sense with a period of 5.27 hours and its geometric albedo is 0.17. Good observing opportunities in late 1995 and several months in 1998 will allow these physical parameters to be further refined. At the time of the NEAR spacecraft arrival in early 1999, the Eros ephemeris uncertainties will be less than 50 km based on ground-based astrometric observations alone.

INTRODUCTION

The discovery of asteroid Eros was made on August 13, 1898 by Gustav Witt at Berlin and independently by Auguste H.P. Charlois at Nice, France. Shortly afterward, Eros was recognized as the first asteroid that could approach the Earth.

The discovery by Witt, director of the Urania observatory in Berlin, was accidental. During a routine observing session on the evening of August 13-14, 1898, Witt took a two hour exposure centered upon beta Aquarius to secure astrometric positions of asteroid 185 Eunike. Along with the expected image of Eunike, a 0.4 mm image trail was noted and observations on the following evening identified the object as one of unusually high apparent motion on the sky. Less than two weeks later, Adolf J. Berberich computed a preliminary orbit and noted that the asteroid's perihelion distance was well inside the orbit of Mars. Witt and Berberich broke with what was then the tradition and gave the asteroid a male name, Eros, the Greek god of love, and son of Mercury and Venus. Once the orbit was established, it became apparent that the asteroid was discovered near aphelion and that a particularly close Earth approach (O. 15 AU) must have occurred on January 21, 1894. Several pre-discovery observations were secured from existing plates so that, currently, the astrometric data interval extends back to October 29, 1893.

Short term variations in the apparent magnitude of 433 Eros were noted soon after discovery, in 1901, by E. Von Oppolzer - perhaps the first definite determination that some asteroids have variable light curves [1]. A correct rotation period of about 5 hours was established as early as 1913 by Solon Bailey at Harvard [2].

Historically, Eros has been a very important object for determining the mass of the Earth-moon system and the value of the astronomical unit. Because of its repeated close Earth approaches, the mass of the Earth-moon system could be determined by using astrometric data before and after these approaches to solve for the system mass together with the asteroid's six orbital parameters, During the twentieth century, Eros data were used to determine various values for the ratio of the sun's mass to that of the Earth-moon system. Observations of Eros were also well suited for determining the value of the astronomical unit using either the trigonometric parallax method or the dynamical method. The solar parallax is defined as the angle subtended by the Earth's radius as seen from a distance of 1 AU (about 8.8 arc seconds). As an object like Eros closely approaches the Earth, its apparent position on the plane-of-sky is very sensitive to the observer's location on the Earth's surface so that position observations can be used to solve for the value of solar parallax; given the radius of the Earth (in km), the AU is then determined. The dynamical method of determining the AU depends upon using the astrometric observations of a close Earth approaching object to determine the system mass of the Ear&h and moon. The mass of the Earth-moon system is directly related to the solar parallax value through a combination of Kepler's third law and the equation of the acceleration of gravity at a given geocentric distance. An interesting history of the various trigonometric and dynamical attempts to determine the solar parallax is given by Eugene Rabe [3]. However, with the use of radar to observe the planets, the value of the AU has been refined beyond the accuracy possible using observations of close Earth approaching asteroids.

In his 1963 book entitled "Watchers of the Skies", the noted historian, Winy Ley, commented that "the next close approach of Eros will be in late January 1975, at which time a close approach by a television-equipped planetary probe will certainly be attempted - and possibly even a landing by a manned ship "[4].

PHYSICAL CHARACTERISTICS

Although no space-based observations of Eros were made near the time when Eros made its close Earth approach (0.15 AU on January 23, 1975), an extensive ground-based observation campaign was under taken. This was the closest Earth approach of Eros during the 20th century. During this opposition, it reached apparent magnitude 7, its phase angle (Earth-Eros-Sun) varied from 9 to 44 degrees and the angle between its rotational axis and the Earth line-of-sight varied widely,

Rotation

During the 1974-75 opposition of Eros, more than 70 photometric light curves were obtained by researchers. Depending upon the orientation of the rotation axis with respect to the line of sight, the light curve amplitude of Eros can vary by as much as 1.47 magnitudes, a factor of 4 in light flux (see Figure 1). Light curves of Eros also show a characteristic double maximum (see Figure 2). The object is likely to be elongated. Extensive photometric studies have defined the rotation period extremely well and provided rotation pole coordinates that do not suffer from the north-south ambiguity that is often the case for asteroids.

The rotation periods, in hours, as determined by several researchers, are given below. Rotation is in a direct sense (counter clockwise as seen from the north) and the pole coordinates are given in the same coordinate system (B1950) as reported in the noted references. The given uncertainties appear in parentheses .

Table 1. Rotation Characteristics for Asteroid 433 Eros

Period (hrs) (Sidereal)	Pole Position (RA, Dec.)	Pole Position (Long., Lat.)	Reference
	4 +43	23 (14) +37 (14)	[5]
5.270112 (0.000120)		22 (Io) 9 (10)	[6]
5.27016 (0.00096)		17 (1) 10 (4)	[7]
	10.7 (1) +14.9 (3.4)	15.4 (2.2) 9.3 (3.8)	[8]
5.270376 (0.000056)		16 (3) 12 (1)	[9]

The rotation period of Eros is about 5.3 hours, two hours less than the geometric mean of all near-Earth asteroids and some 4.6 hours less than the mean rotation period for all asteroids [10].

Size and Photometric Characteristics

Several size estimates have been generated for Eros using various types of observations made in 1975 and 1981. The techniques employed include photometry [8,9], thermal radiometry [13, 14], speckle interferometry [5], polarimetry [1 2], and radar [11]. In particular, the radar analysis suggests the polar silhouette of Eros has a non-axisymmetric, quasi-trapezoidal shape. A number of the size estimates are given below together with estimates for Eros' geometric albedo and phase coefficient.

Table 2. Size and Photometric Properties for Eros

Size (km.)	Geometric Albedo	Phase Coef. mag./deg.	Reference
41 (3)x 15 (2)x 14 (2)	0.156 (0.010)		[5]
34-37 x 14-18			[11]
21	0.201		[12]
39.3 (2) x 16.1 (0.8)	0.125 (0.025)		[13]
		0.0233	[8]
31 x 12 x 12		0.025	[9]
22 (2)	0.18 (0.03)		[14]

Morphology and Composition

Eros has been identified as a S class asteroid because of its moderate albedo, a relatively red continuum slope and broad absorption features near the 1 and 2 micron regions of its spectrum. Mixtures of olivine, pyroxene and nickel-iron metals are thought to comprise the S-class asteroids. As the most common asteroid type in the inner asteroid belt, one school of thought considers S-class asteroids as the parent bodies of the most common type of meteorites, the ordinary chondrites [15]. Because the spectra of the S-class objects are dissimilar from laboratory spectra of ordinary chondrites, it has been suggested that "space weathering" has altered their spectral features. Another group believes the parent bodies of the ordinary chondrites are not the S-type objects at all but rather the Q type asteroids. Asteroid 1862 Apollo and only a few other objects belong to the Q spectral class. While far less common than the S-type asteroids, these objects have spectra that are similar to those of ordinary chondrites [16]. Ordinary chondrites are thought to represent primitive, largely unaltered bits and pieces left over from the inner solar system formation process. Their chemical composition is similar to that of the sun, for all but the most volatile elements. Great importance is attached to determining whether or not the S-type asteroids are the parent bodies of the ordinary chondrites. If they are, then the S-type asteroids, like Eros, may represent primitive bodies largely unchanged since their accretion. If the S asteroids are not the parent bodies of the ordinary chondrites, they would likely be fragments from a more evolved body that has undergone igneous melting and separation of mineral phases.

There is an unresolved question as to whether Eros is a primitive, undifferentiated body or one that has suffered various degrees of igneous melting to become differentiated. On the basis of its reflectance spectra, Eros has been described as a typical member of a group of differentiated objects that have been heated to the 1000 degree centigrade melting point of silicates [1 O].

Pieters et al note that Eros is composed of an undifferentiated assemblage of moderate to high temperature minerals (iron, pyroxene, and olivine but no carbon). H chondrites are such assemblages, but they note it would be premature to conclude that Eros is an H chondrite [19].

Two of the principal conclusions arising from the 1974-75 observing campaign of Eros were that the surface is uniform, suggesting that it is a single geologic unit and the light curve variations are likely due to the asteroid's shape rather than albedo variations over the surface. These conclusions were drawn because neither the polarization, spectral reflectivity, nor color index changed as the asteroid rotated [8, 12, 19, 21].

However, recent work by Murchie and Pieters suggests that slight variations in the spectrum of Eros are evident as the asteroid rotates [20]. Using near infrared and visible spectra at similar phase angles, they noted differences in the one and two micron absorption bands on opposing hemispheres of Eros. They conclude that the most likely explanation requires there be compositional differences between the two hemispheres of Eros; one is richer in olivine and the other richer in pyroxene. Eros exhibits mineralogical heterogeneity comparable to the greatest that has been well determined on any S asteroid. Ostro et al. used radar data to determine the rough shape of Eros and concluded that one hemisphere was relatively flat while the other was convex [11]. Taking these radar results together with the spectral analysis by Murchie and Pieters, the latter group concludes that the flat face of Eros is rich in pyroxene while the convex face is rich in olivine.

Thermal infrared measurements of Eros, as well as radar observations, favor relatively low values for the thermal conductivity and radar reflectivity [14, 17, 18]. These results suggest that any metallic elements are insulated from one another and would not be present in quantities sufficient to be electrically conducting (as in stony iron meteorites). In addition, radar observations suggest the surface of Eros is rough at scales of 3-70 cm.

With the arrival of the NEAR spacecraft at Eros, the increased spectral and spatial resolution of the multispectral imager and near-infrared spectrometer will allow an investigation into the object's mineralogy and a likely determination as to whether or not the object is heterogeneous. Depending upon the spatial arrangement and geologic context of detected heterogeneities, conclusions can be drawn concerning the origin and evolution of Eros. For example, discrete layers of compositionally similar material would suggest a differentiated body while loose clumps of similar materials might suggest an origin as an undifferentiated rubble pile. Results from the X-ray and gamma ray spectrometers will determine the elemental composition of this S-type object to a level that should allow conclusions to be drawn as to whether or not the S-type asteroids are the parent bodies of the most common meteorites.

Orbit and Ephemerides

Prior to the NEAR encounter in earty 1999, there are two excellent observation opportunities in the Fall of 1995 and several months (Feb. - Nov.) in 1998. The latter opportunity will be best observed in mid-year from the southern hemisphere (see Figure 3). The minimum Earth - Eros distance in 1995 and 1998 will be 0.6 and 0.5 AU respectively.

In mid-1995, there were some 2666 optical astrometric observations of 433 Eros over the interval 1893 Oct. 29-1993 Dec. 1. There are also 2 Doppler and one delay radar observation made during the Jan. 1975 close Earth approach and another Doppler taken during Dec. 1988. The rms residual for all optical observations is 0.83 arc seconds.

Table 3. Orbital elements (J2000) of Eros for an epoch close to the time of the NEAR encounter

Orbit solution No.	21
Planetary Ephemeris:	DE403
Epoch	2451188.5 = 1999 Jan 10.0 (TDB)
Eccentricity	0.22286557
Perihelion distance (AU)	1.13328452
Perihelion passage time	2451441.859413 = 1999 Sep 20.359413 (TDB)
Argument of perihelion	178.611596
Longitude of ascending node	304.430444
Inclination	10.829931
Orbital period (years)	1.76

The orbital characteristics of Eros are presented in Figure 4.

An analysis was undertaken in an effort to understand the ephemeris uncertainties of Eros at the time of the NEAR spacecraft arrival from ground-based observations alone. The analysis information presented below is given in a heliocentric and geocentric reference frame.

The heliocentric RTN coordinate system is defined by a Sun-asteroid unit vector (R), a unit vector normal to R and also normal to the asteroid's orbit plane (N) and by a transverse unit vector (T) that completes the right handed, orthogonal system such that T = N x R. The error ellipse is in the orbit plane and oriented using the angle theta which is measured from R towards T.

In the Earth plane-of-sky (POS) coordinate system, the A axis is parallel to the celestial equator, and positive in the direction of increasing right ascension, the D axis increases in the direction of positive declination and the R axis direction is directed from the Earth to the asteroid. The uncertainty ellipse lies in the plane-of-sky with theta measured from A towards D (clockwise as viewed from Earth).

As well as using all of the optical and radar astrometric data employed in the above orbit determination, some 22 future, simulated observations were used in the uncertainty analysis. These simulated observations were assumed taken over the intervals from 1995 August 29 through 1995 October 28 and from 1998 February 24 through 1998 July 4. The simulated data and the data from 1893-1993 were assumed to have noise values of 1.0 and 1.3 arc seconds respectively. These noise values, and the number of future astrometric positions considered, are very conservative. Even so, the immense amount of data available for asteroid Eros and the fact that much of it was taken during Earth close approaches, results in very low ephemeris uncertainties projected for the time of the NEAR spacecraft arrival.

Table 4. Summary of 433 Eros Ephemeris Uncertainties at the NEAR spacecraft encounter on 1999 Jan. 10. The given values (in km) represent l-sigma estimates of the uncertainty ellipsoid axes in the particular coordinate system.

RTN Coordinate System			orbit Plane Error Ellipsoid Semi Axes		
R	T	N	Major	Minor	Theta
5	29	11	29	5	86°
Plane of Sky Coordinate System			Error Ellipsoid Semi Axes		
A	D	R	Major	Minor	Theta
26	16	6	28	11	260

While ground-based observations in the fall of 1995 and in the spring and summer of 1998 will be used to improve our knowledge of the physical characteristics of asteroid 433 Eros, the following working model is suggested for NEAR mission analysis studies.

Table 5. Working Model for Asteroid 433 Eros

Spin period (hours)	5.2703 (direct)
Spectral type	s
Geometric albedo	0.17
Shape/size (km)	40.5 (3.1) x 14.5 (2.3)X 14.1.(2.4)
GM (km^3/sec^2)	8.66×10^{-4} (assumed density= 3 g/cc)
Spin pole location	
Ecliptic long.	16° (3°)
Ecliptic lat.	+12° (1°)
Magnitude parameters	
H	11.16
G	0.46

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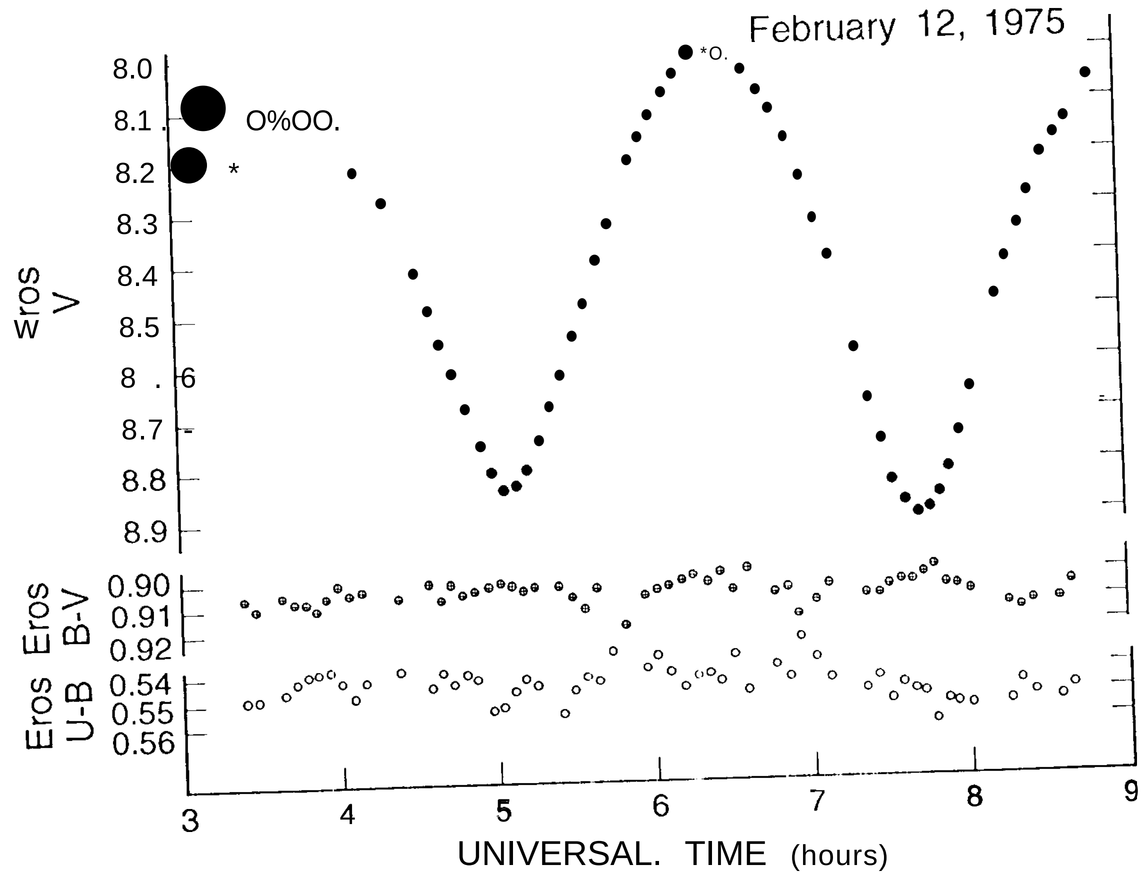
Figures.

1. Observed visual magnitude of asteroid 433 Eros as a function of time on February 12, 1975. While there are obvious visual brightness changes noted as Eros rotates, the U-B and B-V color indices do not change significantly. From a diagram by R. Minis, Lowell Observatory, in the journal, Icarus.

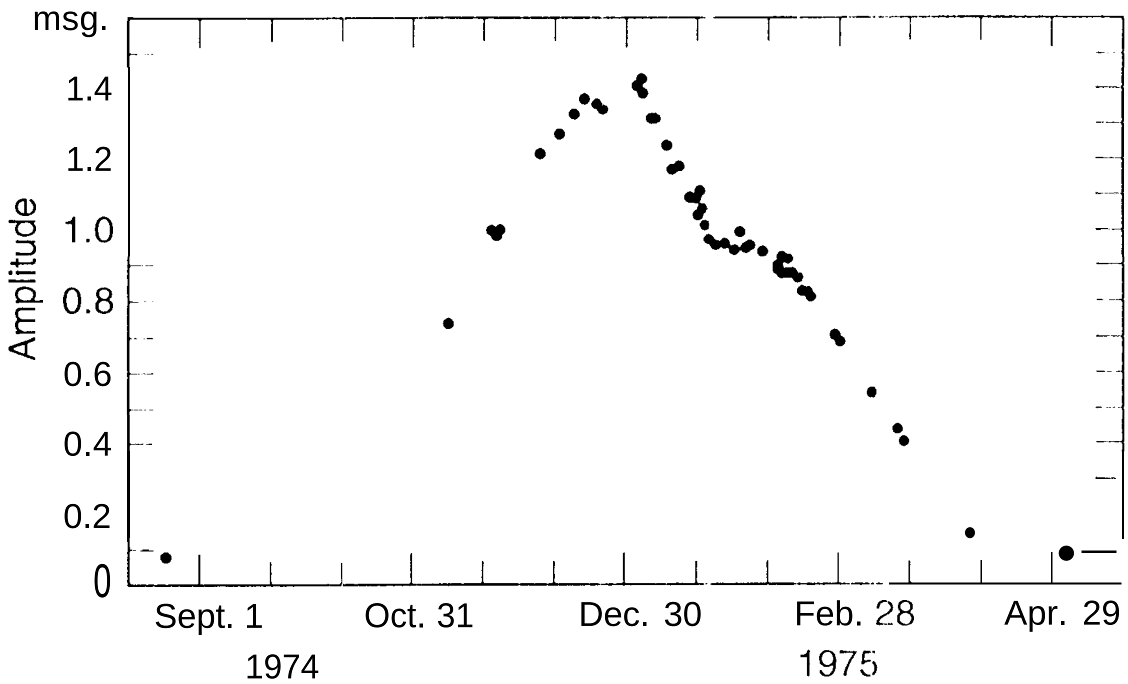
2. Light curve amplitude of Eros as a function of time. The amplitude of Eros' rotational light curve variation increased from 0.1 magnitude in late August 1974 to over 1.4 magnitude in late December when the Earth passed through the equatorial plane of the asteroid. From a plot by L. Dunlap in the journal Icarus.

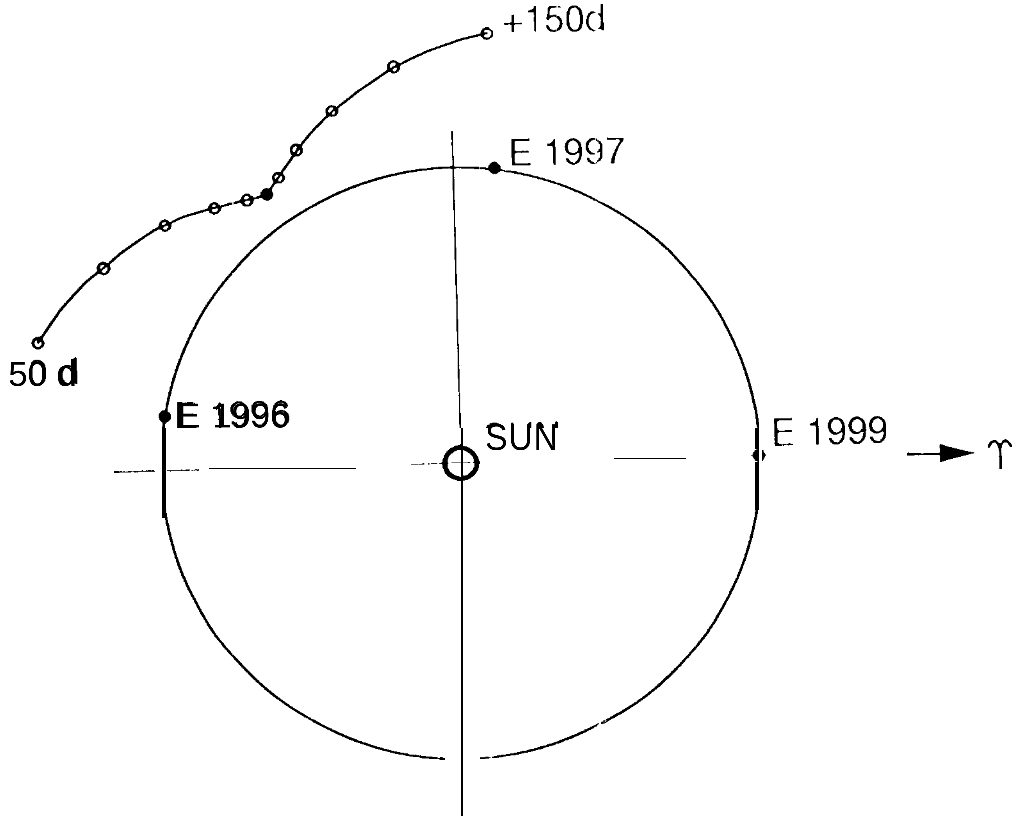
3. Observing conditions for asteroid Eros. This plot was drawn in a rotating coordinate system so that the Sun-Earth line is fixed. The peculiar apparent motion of Eros on the sky is represented from 150 days before perihelion (-1 50d) to 150 days after perihelion (+150d). Small circles are drawn every 30 days along the asteroid's path. The sun's position is in the center of the circle with the Earth's fixed position denoted with an "E" for each perihelion passage (1996 March 12; 1997 December 16; 1999 September 20). Note that Eros will be most easily observed before perihelion in late 1995 and early 1996 as well as after perihelion in early 1998.

4. Orbital diagram for asteroid 433 Eros.

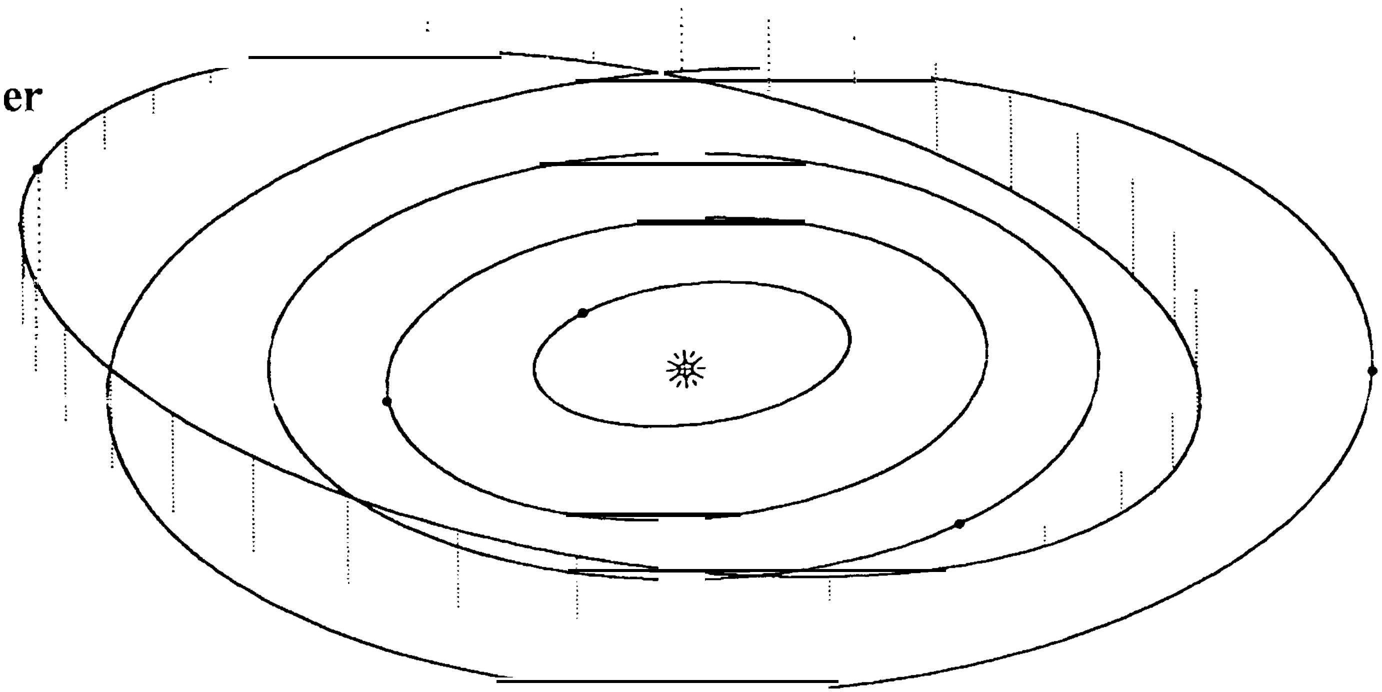


February 12, 1975
Eros V
Eros B-V
Eros U-B
UNIVERSAL. TIME (hours)


msg.
Amplitude
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Sept. 1
Oct. 31
Dec. 30
Feb. 28
Apr. 29
1974
1975


+150d
E 1997
50 d
E 1996
SUN
E 1999
♈

Asteroid 433 Eros



Orbita period; .76 years
Perihelion ista ce . 3 AU