RADAR OBSERVATIONS OF ASTEROID 1999 JM8

LANCE A. M. BENNER[1]*, STEVEN J. OSTRO[1], MICHAEL C. NOLAN[2], JEAN-LUC MARGOT[3], JON D. GIORGINI[1], R. SCOTT HUDSON[4], RAYMOND F. JURGENS[1], MARTIN A. SLADE[1], ELLEN S. HOWELL[2], DONALD B. CAMPBELL[5], DONALD K. YEOMANS[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099

[2]Arecibo Observatory, National Astronomy and Ionosphere Center, Arecibo, PR 00612

[3]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125

[4]School of Electrical Engineering and Computer Science, Washington StateUniversity, Pullman, WA 99164-2752

[5]National Astronomy and Ionosphere Center, Space Sciences Building, Cornell University, Ithaca, NY 14853

Submitted to *Meteoritics and Planetary Science*
November 2001
Revised: January 2002

29 manuscript pages (including cover sheets, tables, and figure captions)
7 tables
6 figures

*Correspondence author:
Dr. Lance A. M. Benner
Mail Stop 300-233
Jet Propulsion Laboratory
Pasadena, CA 91109-8099

email: lance@reason.jpl.nasa.gov
phone: 818-354-7412
fax: 818-354-9476

ABSTRACT

We report results of delay-Doppler observations of 1999 JM8 with the Goldstone 8560 MHz (3.5 cm) and Arecibo 2380 MHz (13 cm) radars over 18 days in July-August 1999. The images place thousands of pixels on the asteroid and achieve range resolutions as fine as 15 m/pixel. The images reveal an asymmetric, irregularly shaped object with a typical overall dimension within 20% of 7 km. If we assume that 1999 JM8's effective diameter is 7 km, then the absolute magnitude, 15.15, and the average Goldstone radar cross section, 2.49 km^2, correspond to optical and radar albedos of 0.02 and 0.06, establishing that 1999 JM8 is a dark object at optical and radar wavelengths. The asteroid is in a non-principal axis spin state that, although not yet well determined, has a dominant periodicity of about 7 days. However, images obtained between July 31 and August 9 show apparent regular rotation of features from day to day, suggesting that the rotation state isn't far from principal axis rotation. 1999 JM8 has regions of pronounced topographic relief, prominent facets several kilometers in extent, numerous crater-like features between ~100 m and 1.5 km in diameter, and features whose structural nature is peculiar. Arecibo images provide the strongest evidence to date for a circular polarization ratio feature on any asteroid. Combined optical and radar observations from April 1990-December 2000 permit computation of planetary close approach times to within ± 10 days over the interval from 293 to at least 2907, one of the longest spans for any Potentially Hazardous Asteroid. Integration of the orbit into the past and future shows close approaches to Earth, Mars, Ceres, and Vesta, but the probability of the object impacting Earth is zero for at least the next nine centuries.

INTRODUCTION

1999 JM8 was discovered by LINEAR on May 13, 1999, fortuitously more than two months prior to an encounter within 0.057 AU (22 lunar distances) of Earth in July 1999, when it reached visual magnitude 14. It originally had been discovered at Palomar in April, 1990 by E. F. Helin and designated 1990 HD1, but was lost. M. Hicks, B. Buratti, and M. Hanner (pers. comm.) obtained photometric colors, vis-IR spectroscopy, and thermal infrared radiometry suggesting that 1999 JM8 is a C- or X-type (i.e., E-, M-, or P-type) object; subsequent vis-IR observations obtained by one of us (E. S. H.) at McDonald Observatory yielded a spectrum more consistent with an EMP-type object. Photometry obtained by L. Sarounova, P. Pravec, Y. Krugly, V. Shevchenko, S. Mottola, F. Lahulla, and M. Hicks (P. Pravec, pers. comm.) between July 3.0 and 21.9 indicated that 1999 JM8 is a very slow rotator. Pravec *et al.* estimated a synodic rotation period of 5.7 ± 0.2 days. The slow rotation period indicated that the echoes would be very strong and that observations on many days would be necessary to obtain thorough coverage in rotation phase. Consequently, prompt communication of the slow rotation period was invaluable for planning the radar observations. Table 1 summarizes the asteroid's optically-determined physical properties.

OVERVIEW OF THE RADAR EXPERIMENT

The asteroid's close approach, large size, and extremely slow rotation provided an outstanding radar opportunity and we observed 1999 JM8 at Goldstone and Arecibo on 18 days between July 18 and August 9, 1999. Orbit solution JPL #15, used for the initial radar detection at Goldstone on July 18, was very good due to the 9-year arc of optical astrometry. Due to problems with the delay-Doppler data acquisition system, on July 18-19 we obtained only CW (continuous wave; i.e. Doppler-only) echoes. On July 20 we started with 2 CW transmit-receive cycles (runs), measured a Doppler correction, and then estimated the range with coarse-resolution 10 and 11 μs (1500 m and 1650 m resolution) setups. We completed that 70 minute set of observations (track) with two imaging runs that resolved the target into about twenty 150-m range cells. We updated the orbit solutions several more times during the experiment; after July 20 range drift due to the ephemeris was imperceptible. Table 2 summarizes the Goldstone and Arecibo observations.

After July 20, our strategy during the Goldstone tracks was to do one or two CW runs to verify that we had echoes and then devote the rest of the track to the finest resolution imaging permitted by the signal-to-noise ratio. For the final Goldstone tracks on August 7 and 8, the asteroid was ~50% farther away than at the closest approach, so we used a coarser resolution of 0.25 μs x 0.075 Hz. However, this still placed thousands of pixels on the target.

At Arecibo we used two imaging data acquisition systems: the Caltech Baseband Recorder (CBR), which was designed for observing pulsars and was made available to us by Stuart Anderson, and a new system (the Portable Fast Sampler, or PFS) that was then under development. We used both systems on each day, but the analyses reported here utilize the CBR data exclusively due to the modestly stronger signal-to-noise ratio (SNR) and the CBR's dual-polarization capability. The range resolution on all days was 0.1 μs and the frequency resolution varied from 0.010 Hz to 0.006 Hz depending on the date (Table 2).

ASTROMETRY & ORBIT REFINEMENT

Table 3 lists 1999 JM8 radar astrometry and best-fit residuals for a post-experiment orbit solution and Table 4 lists the estimated orbital elements and their uncertainties. Combined optical and radar observations from April 1990-December 2000 permit reliable computation of the orbit over the interval from 293 to at least 2907, one of the longest spans for any near-Earth asteroid. Here "reliable" means that the 3-σ uncertainty in the epochs of close approaches is less than 10 days.

Table 5 shows approaches within 0.1 AU of Earth, Mars, Ceres, and Vesta and within 1.0 AU of Jupiter during that interval. There are multiple encounters with Earth, Mars, Ceres, Vesta, and Jupiter, but in the next millennium all the encounters are with Earth, none closer than that in 1999. The impact probability through 2907 is effectively zero.

DISC-INTEGRATED PROPERTIES

Our methods of radar data reduction and analysis follow those described in detail by Ostro e*t al.* (1992, 1996). In Doppler-only observations, echoes were received simultaneously in the opposite (OC) and same (SC) senses of circular polarization as the transmission. σ_{OC} is the OC radar cross section; uncertainties in σ_{OC} are dominated by systematic pointing and calibration errors that are typically between 20 and 50%. The circular polarization ratio SC/OC is a gauge of near-surface roughness at spatial scales near an order of magnitude of the radar wavelength (12.6 cm at Arecibo and 3.53 cm at Goldstone). For SC/OC, systematic effects cancel and most remaining statistical errors propagate from receiver thermal noise.

Table 6 summarizes 1999 JM8's 3.5 cm disc-integrated properties and Fig. 1 shows a collage of CW spectra obtained at Goldstone on each day. The 3.5 cm cross section varies significantly from day-to-day and we obtain an average of 2.5 km^2, to which we assign an uncertainty of 35%. During the course of the experiment the bandwidths increased from about 1.5 Hz to 3.4 Hz, suggesting a more equatorial view on later dates and/or an irregular shape. 1999 JM8's average SC/OC = 0.19 ± 0.01 is less than the median of ~0.28 estimated for all radar-detected NEAs, so the the object's near-surface roughness is somewhat less than average.

DELAY-DOPPLER IMAGES

Figure 2 shows a chronological sequence of OC delay-Doppler images obtained between July 20 and August 9. Each frame has the same range and radial velocity dimensions. Most of the images are sums of all the highest resolution runs on each day. Due to the well-known north-south ambiguity inherent with delay-Doppler images, we do not know in which hemisphere individual features occur.

Table 7 gives the asteroid's visible range extents and bandwidths measured from the images on each day. The maximum extents are 5.3 km on August 6 and 3.6 Hz (when adjusted to Goldstone's frequency of 8560 MHz) on August 5. The Arecibo images generally show larger range extents than the Goldstone images, perhaps due to the greater sensitivity at Arecibo and/or due to differences in the asteroid's orientation. On August 1, the only day of overlap between the two observatories, the visible range extent in the Arecibo image is about 0.3 km deeper. The images have an average visible range extent of 3.6 km. Based on our experience with shape inversions of other objects, the visible range extent typically is about one-half of the true range extent; if so, then 1999 JM8's true range extent is about 7 km.

Prominent features in the images appear to rotate by about 50° from day-to-day between July 31 and August 9, suggesting that 1999 JM8 had an apparent rotation period of about one week and that the subradar latitude was within a few tens of degrees of zero during that interval. Images obtained on July 24, August 1, and August 8 show very similar surface features, suggesting that the rotation phases were nearly the same and offering additional support for an apparent rotation period of about seven days. We searched for evidence of rotation among images obtained on the same day and found it on several days (e.g., on August 5 and 8, the longest Arecibo and Goldstone tracks; Fig. 3) at rates consistent with those seen from day to day.

The rotation period evident in the delay-Doppler images is somewhat longer than the 5.7-d estimate obtained by Pravec *et al.* The difference could be due to the effects of the large solar phase angles between 85-120° on dates when the lightcurves were obtained (1999 July 3-21) and the asteroid’s irregular shape, sky motion, and the rotation state (which is discussed below). Given that we can see rotation directly in the delay-Doppler images, in the analysis below we adopt a rotation period of 7 days as our nominal rotation period estimate. A more precise estimate of the spin state will require inversion of the delay-Doppler images and lightcurves.

Because the July 31-August 9 image sequence is strikingly similar to what we'd expect for a normal rotator viewed close to its equatorial plane, we adjusted the images to the same delay and Doppler scales and aligned them by hand to construct an estimate of 1999 JM8's pole-on silhouette (Fig. 4). The silhouette's elongation is about 1.15, a value that ranks near the lower end of the distribution of radar-derived NEA elongations, which have a mean and rms dispersion of 1.6 ± 0.4 (Ostro *et al.* 2001).

SPIN STATE

Is 1999 JM8's rotation principal axis (PA) or non-principal axis (NPA)? Let us pretend that it is principal axis and then examine the images to see if this assumption is valid. The apparent rotation vector $\mathbf{W}_{app}$ is the vector sum of the intrinsic rotation $\mathbf{W}_{int}$ and the contribution due to sky motion $\mathbf{W}_{sky}$. Figure 5 shows that the angular rate of motion varied from a minimum of about 2° per day to a maximum of about 7° per day. Between July 20-28, the appearance of the asteroid changed substantially from day to day (it is difficult to identify the same features on adjacent days), indicating considerable apparent daily rotation. Between July 31 and August 9 we observe about 50° of rotation per day, so W_{int} dominates over W_{sky} and $W_{app} \sim W_{int}$.

Delay-Doppler images obtained on July 24 and August 1, days in which the sky motion was about 4° and 7°, have very similar orientations but their bandwidths differ by about a factor of two:

$B_{jul24}/B_{aug1} = B_1/B_2 = (1.7 \pm 0.15 \text{ Hz})/(3.3 \pm 0.15 \text{ Hz}) = 0.52 \pm 0.05.$

If the spin is PA, this bandwidth change was due to the change in subradar latitude δ from July 24 to August 1. Expressing the apparent rotation period P in hours and the diameter D in km gives the 8560 MHz bandwidth B in Hz: $B = 100\ D \cos\delta/P$, so the ratio of the bandwidths $B_1/B_2 = \cos\delta_1/\cos\delta_2 = 0.52$ could be caused by a change in $\cos\delta$ due to about 50° of sky motion between the two days. Furthermore, $|\delta_2| \geq 0°$ and $|\cos\delta_2| \leq 1$, so $|\cos\delta_1| \leq 0.52$ and $|\delta_1| \geq 59°$.

However, visual inspection of features in the July 24 and August 1 images suggests that the orientations of 1999 JM8 on those days differ by less than 10° of latitude. To quantify the latitude difference $|\delta_1 - \delta_2|$, we measured the locations in range relative to the leading edge of several features that are visible in images on both July 24 and August 1. The features differ in range by ~0.5 μs to ~1 μs, which is 1-2 range pixels at the July 24 resolution, indicating that the displacement in latitude is small. We quantified the displacement further by computing the latitude difference that is implied by 0.15 km (1 μs) of displacement on a sphere ~7 km in diameter. We are convinced that 10° is a conservative number unless the subradar latitude on July 24 was within a few degrees of the pole, which is impossible because that would imply an object larger by a factor of several than the one observed.

Let us adopt the upper limit on the change in $|\delta_1 - \delta_2|$ of 10° and explore its implications:

First $\qquad \cos\delta_1 = (0.52) \cos\delta_2$

Then $\qquad \cos(\delta_2 + 10°) = (0.52) \cos\delta_2$

After applying a trigonometry identity and some algebra we obtain:

$$\sin\delta_2/\cos\delta_2 = \tan\delta_2 = (\cos 10^\circ - 0.52)/\sin 10^\circ$$

So $$\delta_2 = 69.5^\circ$$

Therefore: $$\delta_1 = \delta_2 + 10^\circ = 79.5^\circ$$

That is, principal axis rotation requires that the subradar latitude had an absolute value of at least 79.5° on July 24. If $|\delta_1| \geq 79.5^\circ$ on July 24, then the ~7 d rotation period evident in the images and the bandwidth of 1.7 Hz constrains the diameter:

$$D \geq (1.7\ \text{Hz})(\sim 7\ \text{d})(24\ \text{h/d})/(100 \cos 79.5^\circ)$$

$$D \geq 15.7\ \text{km}$$

However, the visible range extents, which presumably show about one-half of the true range extent, average only 3.6 km (Table 7), which is inconsistent with $D \geq 15.7$ km. Thus, the assumption of principal axis rotation leads to a contradiction and we are forced to conclude that 1999 JM8 is a non-principal axis rotator.

We also conducted a search for principal axis spin states in which sky motion was explicitly included. We searched for spin state/diameter combinations that match the observed bandwidths and produce similar longitudes on July 24, August 1, and August 8, days when the orientation of 1999 JM8 is very similar. The search covered the entire sky at 5° intervals, rotation periods between 5.0 and 18.0 days at intervals of 0.1 days, diameters between 3.5-10.0 km in 0.1 km increments, and the search assumed that 1999 JM8 is spherical.

We found that principal axis spin states fit the observations only if the absolute values of the subradar latitudes are about 55-63° on July 24, about 15-25° on August 1, and 5-15° (and on the opposite side of the equator relative to the other two days) on August 8. That is, in order for principal axis rotation to fit the observations, the subradar latitudes on July 24 and August 1 must differ by 30-40°. However, that contradicts the striking similarities seen in the images, which indicate a latitude difference on those days of much less than 30°.

Stated more succinctly, the July 24 and August 1 images clearly show the same side of 1999 JM8 but have bandwidths that differ by nearly a factor of two. Given that W_{int} dominates over W_{sky}, the position of the spin vector in the asteroid had to be different on the two days; that is, the spin must be NPA. On the other hand, the apparent regular rotation of features in images between July 31-August 1 suggests that W_{int} has a period of about one week and that the rotation state isn't far from principal axis rotation. PA rotation would be admissible if the latitude difference between July 24 and August 1 was 30-40°, so the upper bound of 10° on the difference in latitudes suggests that the spin axis moved by at least 20° in seven days. Refined estimates of the spin state will require shape inversion, which is beyond the scope of this paper.

Several other slowly rotating asteroids are suspected of being NPA rotators. 4179 Toutatis is in a well-defined NPA state (Hudson and Ostro 1995) and NPA rotation is strongly suspected for 253 Mathilde (Mottola *et al.* 1995), 288 Glauke (Harris *et al.* 1999), 3288 Seleucus (Harris *et al.* 1999), 4486 Mithra (Ostro *et al.* 2000), and 1999 GU3 (Pravec *et al.* 2000).

SURFACE FEATURES

The sequence of daily images from July 31-August 9 show a clear progression of familiar prominent features. 1999 JM8 has an irregular, asymmetric shape characterized by regions of pronounced topographic relief, prominent facets several kilometers in extent, at least one large concavity, and numerous smaller concavities. On July 23, 24, August 1, 2, 8, and 9, the leading edge is rounded, suggesting a spheroidal shape at those aspects. In contrast, on July 20, 27, 28, August 5, and 6, the leading edge is more angular and the July 20 image is almost triangular.

On several days the leading edges show relative topographic relief of up to several hundreds of meters. For example, the July 27 leading edge shows a pronounced "peak" extending ~400 m toward the radar. The July 28 leading edge has a "valley" that is 100-300 m more distant in range than the two adjacent "hills."

There is a large, nearly flat feature evident on the leading edges of the July 31 and August 1 images. On July 31 the feature extends across the middle of the leading edge and on August 1 it is on the right (receding side), with a range extent of at least 2 km. The August 4-6 images show a prominent, nearly flat region on the leading edge that, as seen in the August 6 image, has a range extent of at least 5 km.

A prominent relatively dark feature, apparently a 2-km-diameter concavity, is near the center of the trailing edge on July 24, August 1, 2, 8, and 9. It is the largest concavity evident in the images.

Other circular to ellipsoidal and relatively dark features are probably impact craters; they have diameters ranging from about 100 meters to about 1 km. One of the smallest, near the center of the July 28 image, is surrounded by a relatively bright annulus that is reminiscent of the relatively bright ejecta deposits seen near impact craters in Arecibo delay-Doppler images of the Moon (Thompson *et al.* 1981) and Venus (Campbell *et al.* 1990). Two large, kilometer-sized crater-like structures are particularly prominent on July 24, 31, Aug. 1, 2, and 8.

POLARIZATION SIGNATURE

Figure 6 shows daily sums of SC, OC, and SC/OC images obtained at Arecibo. The images show only those pixels in which the echo power in both polarizations exceeds 3-standard deviations. Each ratio image shows a region of relatively low SC/OC ~ 0.1 at the echo's leading edge and a general pattern of increasing SC/OC (to ≥ 0.5) as a function of increasing range toward the trailing edge. This pattern is similar to that seen in SC/OC images from Toutatis (Ostro *et al.* 1999). Low SC/OC at the leading edge reveals a smooth, specularly reflecting surface that preferentially returns OC echo near normal incidence. We also investigated thresholds of 5 and 10 standard deviations and found that although the number of points decreases with each increase in the threshold, the patterns in the distribution of SC/OC do not change significantly.

Near the trailing edge of the August 2 image is an ellipsoidal region of about 200 pixels with lower SC/OC than its surroundings. We filtered the image with a 10 x 10 pixel boxcar and found that SC/OC = 0.08 ± 0.01 within the region and 0.24 ± 0.01 at more positive and negative Doppler frequencies in the same span of range gates. The ellipsoidal structure is within an oval region that is relatively bright in both the SC and OC images. Its origin is not clear, and due to the north-south ambiguity, it is possible that there are contributions to the SC/OC difference from both hemispheres. One plausible explanation is that this may be a crater wall oriented at a low incidence angle that gives more specular reflections than adjacent regions. This may be evidence for a polarization ratio feature, which, if true, would be the first observed on an asteroid. There are also suggestions of narrow regions of lower SC/OC on August 1, 2, 3, and 5 adjacent to arcuate features that may be crater rims.

DISCUSSION

If, as we suspect, 1999 JM8's effective diameter is ~7 km, then the absolute magnitude of 15.15 (Table 1) corresponds to a very low optical geometric albedo $p_V = 0.02$. This albedo and the optical spectrum strongly suggests that 1999 JM8 is a P-class object. The average Goldstone radar cross section, 2.49 km^2, corresponds to a radar albedo of 0.06, an estimate that overlaps the radar albedos for C-, S-, and BFGP-type main-belt and near-Earth asteroids.

How did the NPA rotation originate? Perhaps 1999 JM8 is a collisional fragment that was excited into NPA rotation during its dispersal from a larger progenitor, either directly into an NPA rotation state (Giblin and Farinella 1997, Asphaug and Scheeres 1999) or due to gravitational interactions with other fragments and/or the parent body (Scheeres *et al.* 2000). Alternatively, perhaps the NPA rotation was caused by an impact into the asteroid or by gravitational torques during one or more very close passes by Earth or another planet (Scheeres *et al.* 2000). The presence of at least three kilometer-sized concavities that appear to be impact craters is consistent with the hypothesis that the NPA rotation was induced by impacts, but the concavities do not rule out the other mechanisms. Perhaps a combination of these mechanisms is responsible.

Another viable explanation is that the NPA rotation could be the result of (or was modified by) outgassing if 1999 JM8 was once a comet. There is a precedent for this conjecture: comet Halley, which is known to be an NPA rotator (Belton 1990; Belton *et al.* 1991). 1999 JM8's timescale for damping to principal axis rotation (Harris 1994) exceeds the age of the solar system, so if the NPA rotation was caused by cometary outgassing, it could still be in that state after cometary activity ceased. 1999 JM8's optical albedo is also consistent with the value of ~0.04 estimated for comet Halley (Delamere *et al.* 1986, Sagdeev *et al.* 1986), although some comets have albedos as large as ~0.1.

However, no cometary activity was seen during the 1999 apparition despite extensive spectrophotometric observing campaigns. The most reliable cometary radar albedo available is the estimate of ~0.04 for IRAS-Araki-Alcock (Harmon *et al.* 1989), a result that is comparable to our estimate for 1999 JM8. However, the nominal radar albedo of 1999 JM8 is also consistent with those estimated for primitive B-, F-, G-, and P-type main-belt asteroids (Magri *et al.* 1999). The orbit of 1999 JM8 (a = 2.72 AU, e = 0.644, i = 13.7°) has a Tisserand criterion = 2.988 that is consistent with an origin as a Jupiter-family comet. Still, many asteroids have comparable Tisserand values, so the Tisserand criterion is not compelling evidence for a cometary origin

(Valsecchi *et al.* 1995). Applying the Bottke *et al.* (2001) dynamical analysis to 1999 JM8, W. F. Bottke (pers. comm.) estimated a probability of about 8% that 1999 JM8 is a Jupiter-family comet. Thus, although the evidence favors an origin as a primitive, outer main-belt asteroid, an origin as a comet nucleus cannot be excluded.

Given our images, it seems likely that inversion of the delay-Doppler images can improve constraints on the asteroid's shape significantly and define its spin state, following the example of 4179 Toutatis (Hudson and Ostro 1995). The next radar opportunity is in 2008 when 1999 JM8 will approach within 0.315 AU of Earth. Estimated SNRs during that apparition could approach a few hundred per day and be adequate to refine the spin state.

ACKNOWLEDGMENTS

Part of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). Work at Washington State University was supported, in part, by a grant from NASA. Some of the observations reported here were obtained with the Caltech Baseband Recorder (CBR), whose development was funded by the National Science Foundation. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation and with support from NASA.

REFERENCES

Asphaug E., and D. J. Scheeres 1999. Deconstructing Castalia: Evaluating a post-impact state. *Icarus* **139**, 383-386.

Belton M. J. S. 1990. Rationalization of comet Halley's periods. *Icarus* **86**, 30-51.

Belton M. J. S., W. H. Julian, A. J. Anderson, and B. A. Mueller 1991. The spin state and homogeneity of comet Halley's nucleus. *Icarus* **93**, 183-193.

Bottke W. F., A. Morbidelli, R. Jedicke, J.-M. Petit, H. F. Levison, P. Michel, and T. S. Metcalfe 2002. Debiased orbital and absolute magnitude distribution of the near-Earth objects. *Icarus*, in press.

Campbell D. B., N. J. S. Stacy, and A. A. Hine 1990. Venus: Crater distributions at low northern latitudes and in the southern hemisphere from new Arecibo observations. *Geophys. Res. Lett.* **17**, 1389-1392.

Delamere W. A., H. J. Reitsema, W. F. Huebner, H. U. Schmidt, H. U. Keller, W. K. H. Schmidt, K. Wilhelm, and F. L. Whipple 1986. Radiometric observations of the nucleus of comet Halley. In *20th ESLAB Symposium on the Exploration of Halley's Comet* (eds. B. Battrick, E. J. Rolfe, and R. Reinhard), Vol. 2, pp. 355-357, ESA SP-250.

Giblin I., and P. Farinella 1997. Tumbling fragments from experiments simulating asteroid catastrophic disruption. *Icarus* **127**, 424-430.

Harmon J. K., D. B. Campbell, A. A. Hine, I. I. Shapiro, and B. G. Marsden 1989. Radar observations of comet IRAS-Araki-Alcock 1983 d. *Astrophys. J.* **338**, 1071-1093.

Harris A. W. 1994. Tumbling asteroids. *Icarus* **107**, 209-211.

Harris A. W., J. W. Young, E. Bowell, and D. J. Tholen 1999. Asteroid lightcurve observations from 1981 to 1983. *Icarus* **142**, 173-201.

Hudson R. S., and S. J. Ostro 1995. Shape and non-principal axis spin state of asteroid 4179 Toutatis. *Science* **270**, 84-86.

Magri C., S. J. Ostro, K. D. Rosema, M. L. Thomas, D. L. Mitchell, D. B. Campbell, J. F. Chandler, I. I. Shapiro, J. D. Giorgini, and D. K. Yeomans 1999. Mainbelt asteroids: Results of Arecibo and Goldstone radar observations of 37 objects during 1980-1995. *Icarus* **140**, 379-407.

Mottola S. A., W. D. Sears, A. Erikson, A. W. Harris, J. W. Young, G. Hahn, M. Dahlgreen, B. E. A. Mueller, B. Owen, R. Gil-Hutton, J. Licandro, M. A. Barucci, C. Angeli, G. Neukum, C. Lagerkvist, and J. F. Lahulla 1995. The slow rotation of 253 Mathilde. *Planet. Space Sci.* **43**, 1609-1613.

Ostro S. J., D. B. Campbell, R. A. Simpson, R. S. Hudson, J. F. Chandler, K. D. Rosema, I. I. Shapiro, E. M. Standish, R. Winkler, D. K. Yeomans, R. Velez, and R. M. Goldstein 1992. Europa, Ganymede, and Callisto: New radar results from Arecibo and Goldstone. *J. Geophys. Res.* **97**, 18227-18244.

Ostro S. J., R. F. Jurgens, K. D. Rosema, R. S. Hudson, J. D. Giorgini, R. Winkler, D. K. Yeomans, D. Choate, R. Rose, M. A. Slade, S. D. Howard, D. J. Scheeres, and D. L. Mitchell 1996. Radar observations of asteroid 1620 Geographos. *Icarus* **121**, 46-66.

Ostro S. J., R. S. Hudson, K. D. Rosema, J. D. Giorgini, R. F. Jurgens, D. K. Yeomans, P. W. Chodas, R. Winkler, R. Rose, D. Choate, R. A. Cormier, D. Kelley, R. Littlefair, L. A. M. Benner, M. L. Thomas, and M. A. Slade 1999. Asteroid 4179 Toutatis: 1996 radar observations. *Icarus* **137**, 122-139.

Ostro S. J., R. S. Hudson, L. A. M. Benner, M. C. Nolan, J.-L. Margot, J. D. Giorgini, R. F. Jurgens, R. Rose, and D. K. Yeomans 2000. Radar observations of 4486 Mithra (abstract). *Bull. Am. Astron. Soc.* **32**, 1003.

Ostro S. J., R. S. Hudson, L. A. M. Benner, M. C. Nolan, J. D. Giorgini, D. J. Scheeres, R. F. Jurgens, and R. Rose 2001. Radar observations of asteroid 1998 ML14. *Meteorit. Planet. Sci.* **36**, 1225-1236.

Pravec P., L. Sarounova, L. A. M. Benner, S. J. Ostro, M. D. Hicks, R. F. Jurgens, J. D. Giorgini, M. A. Slade, and D. K. Yeomans 2000. Slowly rotating asteroid 1999 GU3. *Icarus* **148**, 589-593.

Sagdeev R. Z., G. A. Avanesov, Ya. L. Ziman, B. Smith, I. Toth, V. I. Moroz, V. I. Tarnopolsky, B. S. Zhukov, and V. A. Shamis 1986. TV experiment of the Vega mission: Photometry of the nucleus and inner coma. In *20th ESLAB Symposium on the Exploration of Halley's Comet* (eds. B. Battrick, E. J. Rolfe, and R. Reinhard), Vol. 2, pp. 317-326, ESA SP-250.

Scheeres D. J., S. J. Ostro, R. A. Werner, E. Asphaug, and R. S. Hudson 2000. Effects of gravitational interactions on asteroid spin states. *Icarus* **147**, 106-118.

Thompson T. W., S. H. Zisk, R. W. Shorthill, P. H. Schultz, and J. A. Cutts 1981. Lunar craters with radar bright ejecta. *Icarus* **46**, 201-225.

Valsecchi G. B., A. Morbidelli, R. Gonczi, P. Farinella, Ch. Froeschle, and Cl. Froeschle 1995. The dynamics of objects in orbits resembling that of P/Encke. *Icarus* **118**, 169-180.

TABLE 1. Optically-derived physical properties

Property	Value		Reference
H (mag)	15.15	0.10	3
G	-0.09	0.02	3
Period (d)	5.7	0.2	3
Δm (mag)	0.7		3
Taxonomy	C or EMP		1
	EMP		2

References:
1. M. Hicks et al., pers. comm.
2. E. S. Howell, pers. comm.
3. P. Pravec et al., pers. comm.

TABLE 2. Observations.

Resolution µs	x	Hz	RA (˚)	DEC (˚)	Δ (AU)	motion (˚)	OSOD	runs	start stop HHMMSS-HHMMSS
GOLDSTONE JULY 18									
CW		0.977	187.6	59.7	0.100	0.04	15	1	211432-211609
CW		0.244					15	6	212119-213931
GOLDSTONE JULY 19									
CW		0.061	186.5	60.0	0.098	0.54	15	10	014044-021542
CW		0.122					15	3	070604-071410
GOLDSTONE JULY 20									
CW		0.244	182.5	63.5	0.093	0.12	17	2	023155-023633
10	x	6.15					17	3	025009-025802
11	x	2.24					17	1	030858-031029
1	x	0.1					17	2	033703-034149
GOLDSTONE JULY 21									
CW		0.244	173.4	63.5	0.084	0.14	19	1	174136-174257
1	x	0.1					19	2	175851-180305
1	x	0.1					19	14	180541-184433
GOLDSTONE JULY 23									
CW		0.244	163.5	64.9	0.077	0.17	21	1	003648-003803
0.5	x	0.075					21	4	005306-010223
0.5	x	0.075					21	13	010410-013854
GOLDSTONE JULY 24									
CW		0.244	146.0	65.5	0.070	0.60	21	2	165825-170154
10	x	2.46					21	2	172513-172850
11	x	2.24					21	2	174329-174659
0.5	x	0.075					21	49	180151-195954
GOLDSTONE JULY 27									
CW		0.244	118.4	62.0	0.062	0.35	21	2	013115-013422
0.25	x	0.05					21	30	014947-025407
GOLDSTONE JULY 28									
CW		0.244	101.4	55.6	0.058	0.51	23	1	171425-171514
0.25	x	0.05					23	18	173023-180552
0.25	x	0.05					23	25	181013-190102
GOLDSTONE JULY 31									
CW		0.244	81.7	38.7	0.058	0.85	23	2	170111-170404
0.125	x	0.05					23	48	172454-190134
0.125	x	0.05					23	24	190739-195539
GOLDSTONE AUGUST 1									
CW		0.244	78.3	33.9	0.059	1.10	23	2	120321-120617
0.125	x	0.05					23	2	122101-122405

0.125 x 0.05					23	3	122647-123152
0.125 x 0.05					23	45	123337-140627
0.125 x 0.05					23	52	141225-155925
GOLDSTONE AUGUST 7							
0.25 x 0.075	64.1	6.2	0.082	0.11	26	2	171958-172405
0.25 x 0.075					26	14	172616-180409
GOLDSTONE AUGUST 8							
0.25 x 0.075	63.0	3.5	0.087	0.93	26	50	115342-142242
0.25 x 0.075					26	53	142939-170807
0.25 x 0.075					26	6	171246-172906
0.25 x 0.075					26	36	173238-191931
ARECIBO AUGUST 1							
4.0	78.4	34.1	0.059	0.34	21	2	123730-124051
0.1 x 0.0098					21	26	125104-135333
ARECIBO AUGUST 2							
CW	74.9	28.4	0.061	0.34	23	1	123810-123903
0.1 x 0.0094					23	28	130204-135658
ARECIBO AUGUST 3							
CW	72.0	23.2	0.064	0.36	23	2	121929-122235
0.1 x 0.0089					23	31	124312-134900
ARECIBO AUGUST 4							
0.1 x 0.0083	69.5	18.3	0.068	0.04	23	5	132600-133504
ARECIBO AUGUST 5							
CW	67.6	14.1	0.072	0.26	26	1	115436-115540
0.1 x 0.0078					26	35	115814-131950
ARECIBO AUGUST 6							
0.1 x 0.0074	65.9	10.2	0.076	0.08	26	13	123350-130414
ARECIBO AUGUST 9							
0.1 x 0.0060	62.1	1.3	0.091	0.14	26	25	104635-115923

Right ascension, declination, and delta are given at the mid-epoch of each day's observations. Motion indicates the plane-of-sky motion during each track. OSOD refers to the orbit solution computed using the JPL On-Site Orbit Determination software. Runs are the numberof transmit-receive cycles with each setup. Start and stop refer to the UTC epochs at the beginning and end of reception of echoes.

TABLE 3. Radar astrometry.

UTC Epoch	OSOD Soln	Correction	Measurement	+/-	resid.
1999 07 18 21:30:00	15	+1.7 Hz	580912.4 Hz	0.4 Hz	0.175
1999 07 20 02:40:00	17	-0.5 Hz	547278.4 Hz	0.3 Hz	0.125
1999 07 20 03:00:00	17	-3132.5 μs	92.6270694 s	10.0 μs	-2.215
1999 07 21 17:40:00	19	+0.8 Hz	528308.3 Hz	0.4 Hz	0.439
1999 07 24 17:00:00	21	+0.5 Hz	420950.7 Hz	0.3 Hz	0.163
1999 07 24 19:00:00	21	-4 μs	69.426792 s	5.0 μs	2.538
1999 07 27 01:30:00	21	+0.5 Hz	264385.7 Hz	0.3 Hz	-0.272
1999 07 27 02:30:00	21	-20 μs	61.40113 s	5.0 μs	-1.574

Astrometry corresponds to echoes from 1999 JM8's estimated center of mass. The reference point for Goldstone is the intersection of the altitude and azimuth axes of the 70-meter antenna, DSS-14. Residuals are the remaining difference when the best-fit prediction of solution #34 is subtracted from the actual measurements. The range equivalent of 1 usec is 150 meters and the radial velocity equivalents of 1 Hz are 17.6 mm/s at Goldstone's transmitter frequency of 8560 MHz.

TABLE 4. Orbit.

Quantity	Value	Uncertainty
Epoch	2451911.5 JD (= 2001 Jan 02.0)	
Eccentricity (e)	0.64440537378	± 0.0000000086
Perihelion distance (q)	0.96733323427 AU	± 0.0000000156 AU
Perihelion date (T_p)	2451383.7257358508 JD (1999 Jul 24.22574)	± 0.0000052119 d
Long. asc. node (Ω)	134.00962375234°	± 0.0000052995°
Arg. of perihelion (ω)	165.98932252768°	± 0.0000095614°
Inclination (i)	13.7134598550°	± 0.0000029247°
Semimajor axis (a)	2.72032579502 AU	± 0.0000000472 AU
Period	1638.81453203005 d (4.48675103853089 y)	± 0.00004263 d
Mean anomaly	115.93669166356°	± 0.0000030143°

1999 JM8's heliocentric orbital elements (OSOD solution #34) and formal 1-standard deviation uncertainties, estimated using our delay-Doppler radar astrometry (Table 3) and currently available optical astrometry (403 angular measurements from April 29, 1990 to December 31, 2000). The mean post-fit radar residuals are: time-delay -0.417 μs ± 2.57 μs, and Doppler frequency, +0.125 Hz ± .255 Hz. Mean post-fit optical residuals are RA, -0.02" ± 0.54", and declination, -0.03"± 0.63". The r.m.s. of residuals normalized by the assigned measurement uncertainty are (0.368, 0.732, 0.589) for delay data, Doppler data, and total data set (including optical), respectively. Elements are in the coordinate frame of the JPL planetary ephemeris DE405 (ICRF93/ J2000, a quasar-based radio frame, generally within 0.01 arcseconds of the optical FK5/J2000 frame). Angular elements are referred to the ecliptic and mean equinox of J2000.

TABLE 5. Close approaches.

Date	Body	Close-Approach Distance nominal AU	min AU	max AU	V_{rel} km/s	ΔT min	Nsigs
293 Sep 19.76	Jupiter	0.9235	0.9009	0.9460	5.7	5079	3.4E6
412 May 24.48	Jupiter	0.9636	0.9523	0.9748	6.0	3783	1.5E6
507 May 4.44	Jupiter	0.9576	0.9370	0.9779	5.6	4290	7.4E5
584 May 11.34	Earth	0.0599	0.0437	0.0812	13.3	6516	5.9E4
625 Dec 22.81	Jupiter	0.9933	0.9837	0.0029	6.0	2621	1.7E6
756 Aug 1.34	Jupiter	0.9963	0.9788	0.0136	5.7	2641	5.9E5
811 May 11.51	Earth	0.0591	0.0340	0.0881	13.1	6987	2.2E5
1024 Nov 22.16	Mars	0.0591	0.0591	0.0621	15.1	2211	3.3E5
1060 May 10.83	Earth	0.0867	0.0864	0.0887	13.9	2974	9.2E5
1078 Jun 7.22	Mars	0.0510	0.0384	0.0641	14.4	1507	6.0E4
1091 Aug 18.89	Earth	0.0794	0.0759	0.0833	14.4	1039	3.5E5
1105 Aug 28.53	Ceres	0.0883	0.0881	0.0885	14.1	58	3.2E4
1123 Jul 1.11	Vesta	0.0814	0.0770	0.0857	12.6	353	5.9E4
1194 Aug 24.21	Earth	0.0462	0.0454	0.0470	15.0	214	1.7E5
1256 Mar 23.79	Mars	0.0692	0.0658	0.0728	16.1	462	1.6E5
1261 Jun 18.77	Vesta	0.0771	0.0757	0.0785	13.7	275	1.7E5
1269 Jun 4.02	Mars	0.0701	0.0690	0.0712	14.5	319	2.0E5
1318 May 3.59	Mars	0.0919	0.0914	0.0926	14.4	565	4.4E5
1412 Aug 25.85	Earth	0.0459	0.0455	0.0463	15.1	54	1.3E4
1474 Aug 21.81	Earth	0.0546	0.0545	0.0547	14.0	22	1.9E5
1692 Aug 9.95	Earth	0.0963	0.0963	0.0964	13.4	15	7.6E5
1981 Aug 20.29	Earth	0.0665	0.0665	0.0665	13.8	6	5.6E5
1990 Aug 8.41	Earth	0.0335	0.0335	0.0335	12.7	2	6.5E5
1999 Jul 30.40	**Earth**	**0.0568**	**0.0568**	**0.0568**	**12.3**	**0**	**5.4E6**
2137 Aug 1.53	Earth	0.0764	0.0764	0.0764	13.3	6	1.5E6
2573 Aug 11.86	Earth	0.0852	0.0852	0.0852	14.0	5	8.6E5
2791 Aug 15.18	Earth	0.0947	0.0947	0.0947	14.0	15	4.3E5
2831 Jul 26.37	Earth	0.0715	0.0715	0.0715	14.0	12	2.4E5
2907 Jul 20.53	Earth	0.0911	0.0911	0.0911	14.2	3	6.9E4

Note: Close approaches within 0.1 AU of the given body except for Jupiter, which is indicated for approaches less than 1.0 AU, are listed along with nominal, 3-sigma minimum and maximum distances. V_{rel} is the relative velocity at the nominal close approach, ΔT is the 3-sigma uncertainty in the epoch of close approach, and Nsigs is the number of standard deviations required for the uncertainty ellipse to intersect the close-approach body.

TABLE 6. Disc-Integrated 3.5-cm Radar Properties.

Date	runs	FFTs	OC SNR	*B* (Hz)	σ_{OC} (km^2)	SC/OC (+/-0.01)
Jul 18	7	1270	940	1.5	2.96	0.19
Jul 19	10	1576	540	1.3	2.46	0.21
Jul 20	2	154	500	2.0	2.97	0.19
Jul 21	1	140	830	1.7	3.54	0.22
Jul 23	1	132	580	1.6	2.26	0.16
Jul 24	2	162	1100	2.3	2.85	0.15
Jul 27	2	216	520	2.6	1.08	0.18
Jul 28	1	80	5700	2.9	3.02	0.17
Jul 31	2	180	1400	3.3	1.94	0.22
Aug 1	2	192	880	3.4	1.81	0.23
Experiment average					2.49	0.19

The bandwidths were estimated using CW spectra with a resolution of 0.122 Hz. *B* is the echo bandwdith. The cross sections and SC/OC were estimated using a frequency resolution of 1.95 Hz in order to have enough fast-Fourier transform (FFTs) to approach Gaussian noise statistics.

TABLE 7. Delay-Doppler dispersions.

Date	RESOLUTION µs x Hz	DELAY EXTENT (km)	BANDWIDTH (Hz)
GOLDSTONE (3.5 cm)			
Jul 19	CW 0.061	no data	1.3
Jul 20	1.0 x 0.1	2.85	1.8
Jul 21	1.0 x 0.1	2.70	1.6
Jul 23	0.5 x 0.075	2.55	1.43
Jul 24	0.5 x 0.075	4.28	1.65
Jul 27	0.25 x 0.05	3.26	2.40
Jul 28	0.25 x 0.05	3.90	2.65
Jul 31	0.125 x 0.05	3.45	3.35
Aug 1	0.125 x 0.05	4.16	3.05
Aug 7	0.25 x 0.075	2.66	3.15
Aug 8	0.25 x 0.075	3.30	3.38
ARECIBO (12.6 cm)			
Aug 1	0.1 x 0.0098	4.50	3.31
Aug 2	0.1 x 0.0094	4.13	3.17
Aug 3	0.1 x 0.0089	3.71	3.17
Aug 4	0.1 x 0.0083	3.47	3.24
Aug 5	0.1 x 0.0078	4.32	3.63
Aug 6	0.1 x 0.0074	5.27	3.20
Aug 9	0.1 x 0.0060	3.96	3.34

Estimated dispersions include pixels with echo power above the 2-sigma level, except on July 27, 28, and 31, when contiguous pixels with SNRs > 1.0 were used. July 24 and August 1 estimates include the distant arc of pixels at the trailing edge that Arecibo images indicate are real. Arecibo bandwidths have been multiplied by 8560/2380 (the ratio of the Goldstone and Arecibo transmitter frequencies) to facilitate comparison with 3.5 cm results.

FIGURE CAPTIONS

Fig. 1. Weighted sums of Goldstone echo power spectra grouped by observation date between July 18 (top left) to August 1 (bottom right). The spectra have been smoothed to a resolution of 0.5 Hz.

Fig. 2. Sequence of OC delay-Doppler images obtained at Goldstone and Arecibo. In each image range increases from top to bottom and Doppler frequency increases from right to left, so rotation is clockwise. The height in each frame is 6.0 km (40 usec). The images are shown with a Doppler extent of 3.7 Hz when adjusted to a frequency of 8560 MHz in order to facilitate direct comparison between Goldstone and Arecibo images. The images have logarithmic contrast stretches in order to take advantage of the dynamic range. The collage shows one image per day, where each frame is the sum of all the highest resolution images on a given day. On August 1 we imaged 1999 JM8 at both telescopes; the image shown was obtained at Arecibo.

Fig. 3. Difference images obtained on August 5 (left) and 8 (right), the longest tracks at Arecibo and Goldstone. Range increases from top to bottom and Doppler frequency increases from right to left, so rotation is clockwise. The August 5 (Arecibo) image shows the difference between the first (white) and last (black) runs on that day, which were obtained 1.3 hours apart. The August 8 (Goldstone) image shows the difference between the first 17 runs (white) and the last 14 runs (black), which were obtained 7.5 hours apart. Several degrees of rotation are evident in the August 8 image.

Fig. 4. Silhouette of 1999 JM8 using delay-Doppler images obtained between August 1-9 assuming principal axis rotation. Images were cut out from hardcopies and aligned by eye.

Fig. 5. Top: Right ascension and declination of 1999 JM8 at the mid epoch of each track. Observations at Goldstone and Arecibo are indicated with circles and crosses. Middle: Angular rate of sky motion as a function of day-of-year (DOY). Bottom: Angular separation of 1999 JM8 as a function of DOY relative to the first Goldstone track on DOY 199 (July 18).

Fig. 6. Arecibo SC (left), OC (middle), and SC/OC (right) images. The delay-Doppler extents and orientations are the same as in Fig. 2. SC/OC is plotted by adopting a detection threshold per pixel of three standard deviations in both SC and OC images. All other pixels are mapped to white. The color stretch is saturated at SC/OC = 0.5 (black) in order to emphasize the most interesting regions of the dynamical range. An arrow points to a region with relatively low SC/OC on August 2