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Radar observations of Comet P/2005 JQ5 (Catalina)

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Abstract

Arecibo radar observations of Comet P/2005 JQ5 (Catalina) have produced the first delay-Doppler images of a comet nucleus and the first radar detection of large-grain ejection from a Jupiter-family comet. The nucleus is small (1.4 km diameter), rough, and rapidly rotating. The large (>cm) grains have low velocities (∼1 m/s) and a low production rate.

Keywords: Comets; Radar observations; Comets, nucleus; Comets, dust

1. Introduction

We report on recent Arecibo radar observations of the small periodic Comet P/2005 JQ5 (Catalina), henceforth abbreviated JQ5. This was only the 11th comet to be detected by radar and the fourth to show an echo from both the nucleus and large grains. These observations provide the first (albeit crude) delay-Doppler radar images of a comet nucleus and the first radar detection of large-grain ejection from a Jupiter-family comet (JFC).

Although JQ5 appeared asteroidal when it was discovered by the Catalina Survey on May 6, 2005 (Larson, 2005), it was reclassified as a comet after subsequent observations revealed an asymmetric coma (Snodgrass et al., 2005). JQ5 is in a low-inclination (5.7°) orbit with a 4.35-yr period, the fourth shortest of any known comet. The orbital elements give a Tisserand parameter $T_J = 2.98$, which places JQ5 in the Jupiter family. With a perihelion distance $q = 0.826$ AU, it is one of only 13 known JFCs in Earth-crossing orbits.

JQ5 made an unusually close approach to Earth ($\Delta = 0.103$ AU) on June 27, 2005. This was the closest comet approach since that of C/Hyakutake in 1996 and the closest comet to be observed with the Arecibo radar since the 1983 apparitions of C/IRAS–Araki–Alcock and C/Sugano–Saigusa–Fujikawa (henceforth abbreviated IAA and SSF, respectively). The small distance offered a good radar opportunity despite the small (∼1 km) size estimated for this comet on the basis of its low visual magnitude.

2. Observations and results

The observations were made with the S-band (2380 MHz; $\lambda = 12.6$ cm) radar on the 305-m Arecibo telescope. We observed on six dates in 2005: June 11, 24, 25, 27, and July 1, 2. For the first two dates we used an unmodulated or CW (continuous wave) transmission, which yields an echo Doppler spectrum but no delay discrimination. For the last four dates we transmitted a pseudorandom binary phase code (Ostro, 1993) in order to make delay-Doppler images. For all dates we transmitted a circularly polarized wave and received both orthogonal circulars. (As is customary, we denote the two receive polarizations as "OC" for the "opposite circular" sense and "SC" for the "same circular" sense, relative to the transmitted circular sense.) Owing to a klystron failure (in a dual-klystron system), we were limited to an average transmitter power of 450 kW, or half the normal power. Telescope pointing and Doppler/delay drift compensation were done using ephemerides generated at the Jet Propulsion Laboratory (JPL).

An initial CW observation was made on June 11, well before close approach, when the comet was at $\Delta = 0.155$ AU. The spectrum from this date showed a nucleus echo with a Doppler bandwidth of 6 Hz and an OC radar cross section of 0.04 km^2. A second, much stronger, CW detection was made on June 24, by which time the comet had closed to within 0.105 AU. In Figs. 1a and 1b we show the OC and SC Doppler spectra from this date. These spectra were summed over 16 runs (transmit/receive cycles) between 19:33 and 20:29 UT, for a total receive integration time of 26 min. The OC spectrum (Fig. 1a) shows two distinct echo components: (1) a narrow echo from the nucleus, and (2) a broad "skirt" or "coma" echo from large grains in the inner coma. The SC spectrum (Fig. 1b) also shows a clear nucleus echo, but only a hint of a coma echo can be discerned in the noise. The slight (+0.4 Hz) Doppler offset in the nucleus echo represents a small error in the predicted observing ephemeris (which had an a priori r.m.s. Doppler uncertainty of 0.6 Hz). The OC coma echo has the characteristic broad-winged, witch-hat shape seen for other comets (Harmon et al., 2004). This component is well approximated by a Lorentzian curve of the form $a/[1+4(f-f_o)^2/B_h^2]$, where a is the spectrum peak amplitude, f is frequency, f_o is the peak offset, and B_h is the spectrum fullwidth at half maximum. To better show the nucleus echo, we plot in Fig. 1c the June 24 spectra on an expanded frequency scale and with a best-fit Lorentzian coma

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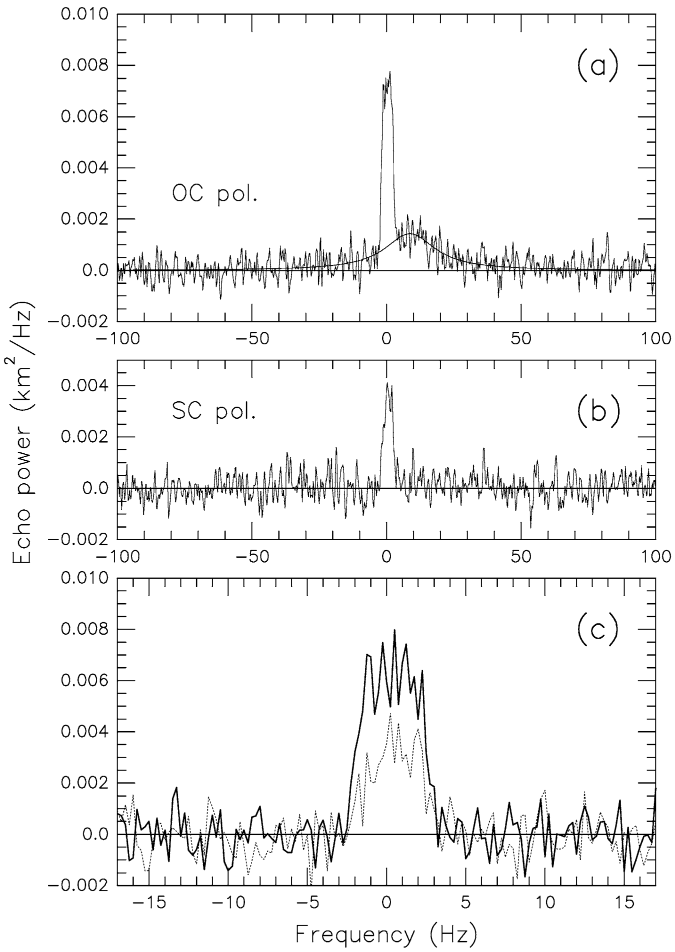

Fig. 1. Echo spectra from the CW observations on June 24 in the (a) OC polarization and (b) SC polarization; the spectra are Hanning smoothed from a raw resolution of 0.25 Hz, and a best-fit Lorentzian curve is shown through the OC coma component. (c) The June 24 echo spectra in the OC (solid line) and SC (dotted line) polarizations, plotted on an expanded frequency scale and with best-fit coma curves subtracted; the spectra have a resolution of 0.25 Hz and are not smoothed.

component subtracted from each polarization. From the spectra in Fig. 1 we computed the OC and SC radar cross sections ($\sigma_{\rm OC}$, $\sigma_{\rm SC}$), circular polarization ratio ($\mu_{\rm C} \equiv \sigma_{\rm SC}/\sigma_{\rm OC}$) and Doppler bandwidths for the nucleus and coma echoes (Table 1). Note that for the coma $\mu_{\rm C}$ we did not use the tabulated $\sigma_{\rm SC}$ (which, like $\sigma_{\rm OC}$, was computed by simply summing the spectra between −50 and +70 Hz), but rather a value estimated by constraining the SC echo to have the same Lorentzian shape and bandwidth as the OC echo. All errors quoted in Table 1 are one standard deviation.

All of the delay-Doppler imaging observations were made using a baud rate of 0.5 µs for the transmitted code, which gives a range resolution of 75 m. The imaging observations were plagued by lightning-induced equipment failures, and only the data from June 27 and July 2 were usable. The OC delay-Doppler images from these dates are shown in Fig. 2. Each of these images is averaged over a full Arecibo transit and is corrected for the echo delay drift associated with ephemeris drift. The June 27 image is from 43 runs between 18:35 and 21:10 UT (69-min integration) and the July 2 image is from 41 runs between 16:50 and 19:25 UT (71-min integration). The images on both dates show weak but clear nucleus detections. (The grain-coma echo would have been too dispersed in delay-Doppler space to have been detectable in these images.)

3. Nucleus

The CW spectrum from June 24 shows that the surface of the JQ5 nucleus is extremely rough. The 50% depolarization ($\mu_{\rm C} = 0.49$) is very high, equalled only by that of Comets C/2004 Q2 (Machholz) (Nolan et al., 2005), Hyakutake (Harmon et al., 1997), and a few near-Earth asteroids (Benner et al., 1997; Harmon et al., 2004). This is an indicator of extremely rough surface texture at wavelength (decimeter) scales. The squared-off shape of the OC spectrum is also suggestive of high roughness. Such limb-brightened scattering is likely dominated by blocky, superwavelength-scale roughness elements that provide a shadowing effect near grazing incidence. Similarly shaped spectra have been seen for all other comets with Doppler-resolved nuclei, regardless of degree of depolarization, implying that extreme blocky roughness is a general property of comet nuclei. Note, however, that the SC spectrum is clearly less squared-off (i.e., more limb-darkened) than the OC spectrum. This suggests that the strong

Table 1
Comet P/2005 JQ5: Radar and physical properties

Parameter	Value
Nucleus	
OC radar cross section, $\sigma_{\rm OC}$ (km^2)	0.0284 ± 0.0057
SC radar cross section, $\sigma_{\rm SC}$ (km^2)	0.0138 ± 0.0031
Circular polarization ratio, $\mu_{\rm C}$	0.49 ± 0.05
Bandwidth, B (Hz)	5.5 ± 0.2
Diameter, D (km)	1.4 ± 0.1
Radar albedo, $\hat{\sigma}$	0.027 ± 0.007
Visual albedo	0.033 ± 0.003
Rotation period, P (h)	<7.0
Grain coma	
OC radar cross section, $\sigma_{\rm OC}$ (km^2)	0.048 ± 0.010
SC radar cross section, $\sigma_{\rm SC}$ (km^2)	0.011 ± 0.005
Circular polarization ratio, $\mu_{\rm C}$	0.20 ± 0.07
Bandwidth (FWHM), $B_{\rm h}$ (Hz)	23 ± 3
Velocity dispersion (FWHM), (m/s)	1.4 ± 0.2

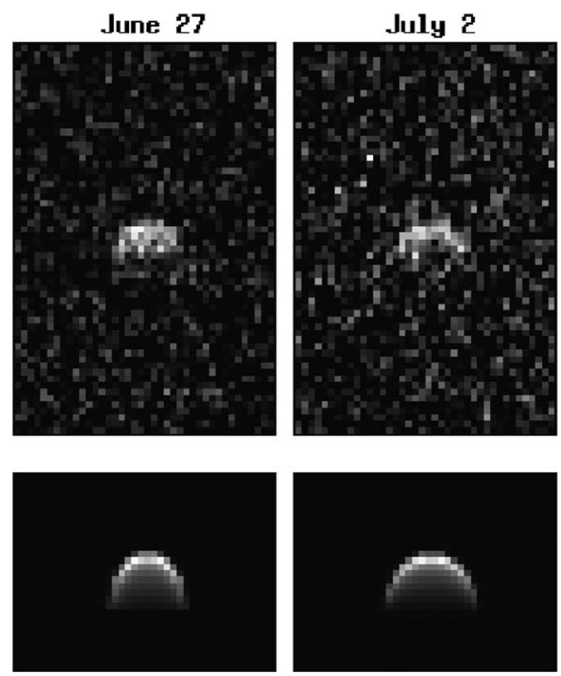

Fig. 2. Gray-scale plots showing the delay-Doppler images from the observations on June 27 (upper left) and July 2 (upper right). Delay increases vertically from top to bottom and has a total span of 30 µs (or 4.5 km in range). Doppler increases horizontally from left to right and has a total span of 19.1 Hz. Each pixel measures 0.5 µs in delay by 0.477 Hz in Doppler. The peak echo strength (in noise standard deviations) is 5.6 for June 27 and 4.8 for July 2. A noise baseline has been subtracted and negative noise pixels clipped. Also shown (lower plots) are the corresponding best-fit templates (see text).

depolarization from this comet comes from a substantial population of smaller (non-blocky) surface roughness elements contributing a more diffractive, limb-darkened scattering without significant shadowing.

JQ5's OC radar cross section ($\sigma_{oc} = 0.0284$) is the smallest yet measured for a comet nucleus. Also, its total radar cross section ($\sigma \equiv \sigma_{oc} + \sigma_{sc} = 0.0422$) is close to that of Comet SSF, whose diameter has been estimated to be slightly less than a kilometer based on infrared measurements (Hanner et al., 1987). Hence, JQ5 is also likely to be a kilometer-size object, which places it at the extreme small end of the cometary nucleus size distribution (Lamy et al., 2004). We can make a direct estimate of the nucleus size from the delay-Doppler images. Since echo is visible in at least five delay pixels, the radius must be at least 375 m. Because one expects the weaker echoes from further back on the comet to be lost in the noise, the true size must be somewhat larger than this. To make a formal size estimate, we least-squares fitted the June 27 and July 2 echoes with delay-Doppler templates computed assuming a spherical nucleus with a $\cos^n \theta$ scattering law. For the fits we varied the nucleus diameter D, Doppler bandwidth B, center-of-mass location, and scattering-law exponent n. The June 27 fit gave $D = 1.48$ km, $B = 5.7$ Hz, and $n = 0.9$, while the July 2 fit gave $D = 1.34$ km, $B = 6.7$ Hz, and $n = 1.0$. Based on these fits and their associated errors, we give $D = 1.4 \pm 0.1$ km as our estimate of the JQ5 nucleus diameter. This is the first direct estimate of the size of a comet nucleus based on radar data alone.

The radar albedo of a nucleus of effective radius R is defined as $\hat{\sigma} = \sigma/\pi R^2$. The best indirect $\hat{\sigma}$ estimates for comet nuclei, computed using independent (non-radar) size estimates, are 0.039 for IAA (Harmon et al., 1997, 1999, 2004) and 0.042–0.055 for Encke (Harmon and Nolan, 2005). Using the 1.4-km diameter estimate gives a radar albedo of $\hat{\sigma} = 0.027$ for JQ5. This, the first direct comet radar albedo estimate, confirms earlier indications that comet radar albedos are much lower than the 0.1–0.3 radar albedos typical of most asteroids (Magri et al., 2001; Harmon et al., 2004). This implies that comets have substantially lower surface densities than asteroids (Harmon et al., 2004). Following arguments given in Harmon et al. (1999, 2004), the radar albedo of JQ5 corresponds to surface densities in the range 0.4–0.8 g cm^{-3}.

The JQ5 diameter estimate also gives a reasonable optical albedo. Using the 1.4-km diameter and the observed visual magnitude, we estimate a visual albedo of 0.033 for the JQ5 nucleus. This is well within the 0.02–0.06 range of visual albedos estimated for comet nuclei (Lamy et al., 2004) and close to the canonical value of 0.04 often used to estimate nucleus sizes based on visual core magnitudes.

Combining our size estimate with the Doppler bandwidth can give a constraint on the nucleus rotation period. The Doppler bandwidth of a spherical nucleus with radius R and rotation period P is $B = 8\pi R \sin\phi/\lambda P$, where ϕ is the angle between the line of sight and the spin axis. Taking $R = 0.70$ km and $B = 5.5$ Hz, then $P < 7.0$ h. This rapid spin rate, though dynamically plausible, places JQ5 at the short end of the comet rotation period distribution (Samarasinha et al., 2004; Lamy et al., 2004). JQ5's small size and fast rotation make it a good candidate for having been spun up by outgassing torques (Jewitt, 1997, 2004), although Yarkovsky effects and tidal interactions with Earth could also have contributed to spinup.

4. Large grains

The grain-coma echo is clearly distinguishable from the nucleus echo by the characteristic broad-winged spectrum and the smaller polarization ratio. The asymmetry of the skirt about the nucleus is typical, and implies anisotropic grain ejection. It also indicates that the grains are mostly ejected outwards in a fan instead of being bound in circumnuclear orbits. The fact that the coma echo is offset toward positive Dopplers ($f_o = +8.7 \pm 1.1$ Hz) means that the overall grain motion was more toward us than away from us at the time of observation. This, combined with the fact that the Sun–comet–Earth angle was 112° on June 24, implies that the "blue-shifted" grains comprising the bulk of the population were ejected at angles greater than 22° from the solar direction (as viewed from the comet).

The 23-Hz B_h of the JQ5 coma echo is the smallest yet measured, implying that the large grains from this comet are slow-moving. The characteristic velocity dispersion $\lambda B_h/2$ is only 1.4 m/s. The next slowest grains are those from 1P/Halley at 2.7 m/s (Campbell et al., 1989; Harmon et al., 2004) and IAA at 4.5 m/s (Harmon et al., 1989, 2004). The four other comets with coma echoes (C/Hyakutake, C/2001 A2, C/2002 O6, C/2004 Q2) have velocity dispersions in the range 11–21 m/s, or an order-of-magnitude faster than for JQ5 (Harmon et al., 1997, 2004; Nolan et al., 2005, 2006). One possible explanation for the slowness of the JQ5 grains is the small nucleus size, since the conventional gas-drag theory of grain ejection has the terminal grain velocity $V_t \propto R^{1/2}$ (Harmon et al., 2004). However, this would not explain the relative slowness of the grains from Halley and IAA, both of which are large comets. A more important determinant of the grain velocity may be the gas mass flux. Higher effective gas fluxes could result from higher volatile concentrations and/or more explosive or highly collimated jetting. This might be consistent with the fact that the two comets with the slowest grains (JQ5 and Halley) are both short-period comets with presumably highly evolved surfaces.

Even if JQ5's grain accelerating ability is weak, there should not be a problem lifting sufficiently large grains against nucleus gravity. Here the small nucleus size should actually help, since the standard model has the maximum liftable grain radius a_m being proportional to R^{-1}. To backscatter efficiently, the largest grains must have a radius of at least $\lambda/2\pi$ (the Rayleigh–Mie transition size), or 2 cm. Given the small nucleus, one could have a gas mass flux two orders of magnitude smaller than the ambient sublimation rate from clean ice and still lift grains this size off the surface. Furthermore, if the nucleus rotates with a <7-h period, the associated centrifugal force will offset over half of the gravitational force at the equator and make grain release that much easier.

The JQ5 coma echo is by far the weakest yet seen, with a cross section of only ~ 0.05 km^2 as compared to the 0.8–32 km^2 range measured for other comets (Harmon et al., 2004). Apparently this comet's large-grain production is low, which is not surprising given the overall weak activity. We can make a crude estimate of the mass-loss rate $\dot{M}$ by comparing with earlier $\dot{M}$ estimates for Comet IAA. For that comet we estimated $\dot{M} \approx 3 \times 10^5$ g/s for $a_m > \lambda/2\pi$ (Harmon et al., 2004). Then, assuming the grains remain intact as they traverse the radar beam, and using the fact that the physical diameter of the beam was 3 times larger and the grain velocity 3 times smaller for JQ5 than for IAA, we estimate $\dot{M} \approx 3 \times 10^5 (0.05/0.8)/9 = 2 \times 10^3$ g/s for JQ5.

Large, slow grains such as those producing the JQ5 coma echo are believed to make up the narrow infrared (IR) dust trails seen for some short-period comets (Eaton et al., 1984; Sykes et al., 1986, 2004; Sykes and Walker, 1992; Kresák, 1993). Kresák (1993) estimates that a production rate of $> 10^{11}$ g/orbit is required to produce a dust trail detectable with the Infrared Astronomy Satellite (IRAS). If we assume a 100-day perihelion passage as the effective grain-producing period for JQ5, then the input to the dust trail would be only about 2×10^{10} g/orbit and, hence, probably undetectable at the IRAS sensitivity. However, a JQ5 dust trail might be detectable with a more sensitive instrument such as the Spitzer Space Telescope, which has an IR sensitivity between 100 and 1000 times that of IRAS. So far, no IR trails have been reported for JQ5, although this comet should be considered a good candidate for future trail searches. In any event, our results show that even the smallest of comets can produce large grains, so it is possible that undetected comets in the JQ5 class might be responsible for some of the IRAS-detected "orphan" trails lacking known parent comets (Sykes et al., 1986, 2004; Sykes and Walker, 1992). Finally, a narrow dust trail might also show up as a detectable meteor stream (Kresák, 1993), which seems a definite possibility for JQ5 given its low-inclination, Earth-crossing orbit.

5. Concluding remarks

Short-period comets are of particular interest, given their suitability as mission targets and their contribution to meteor streams and the interplanetary dust complex. The recent discovery and close passage of JQ5 has given us a fortuitous look at one of the humbler members of this family. Although JQ5 itself does not make another close approach until 2036 ($\Delta = 0.05$ AU), three other short-period comets should be easily detectable in the next five years: 73P/Schwassmann–Wachmann 3 ($\Delta = 0.07$ AU) in 2006, 8P/Tuttle ($\Delta = 0.25$ AU) in 2008, and 103P/Hartley 2 ($\Delta = 0.12$ AU) in 2010. All three are potential imaging targets, although the latter two (Tuttle because of its distance; Hartley 2 because of its suspected small size) are unlikely to yield high-quality images. All three comets are likely producers of large grains, and one (Tuttle) is the parent of its own meteor stream. Hence, coma echoes are possible. It will be interesting to see if any large-grain comae detected from these comets exhibit the same low velocity dispersion seen for those other short-period Comets JQ5 and Halley, or the higher velocities so far only seen for long-period or new comets. We will also be on the lookout for more close apparitions of newly discovered comets, especially those offering good imaging opportunities.

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