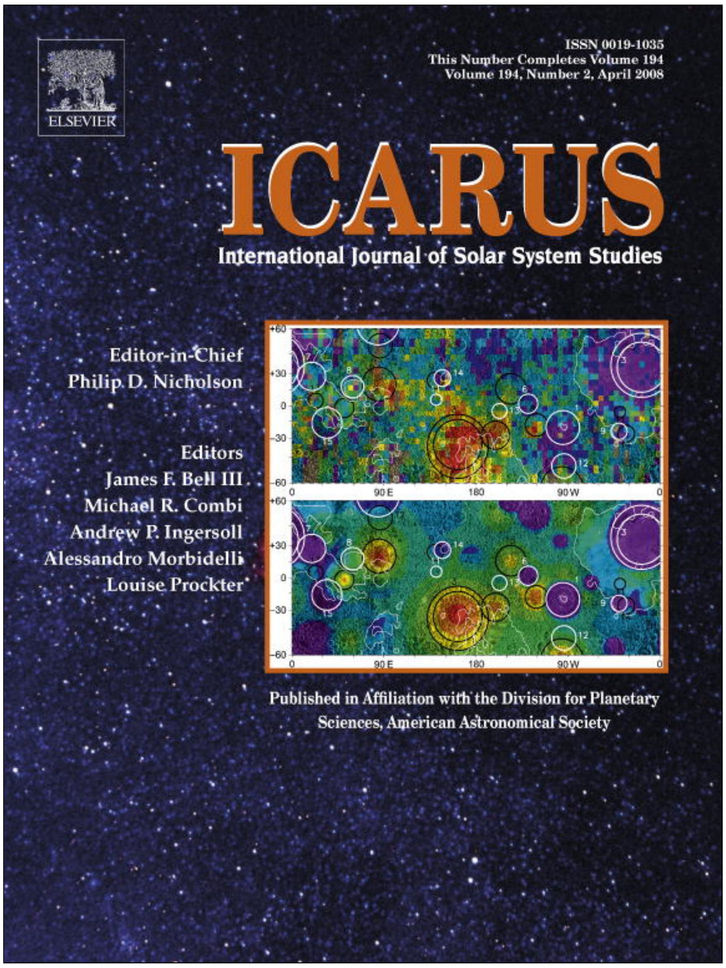

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Note

An upper limit on gas production from 3200 Phaethon

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Abstract

Asteroid 3200 Phaethon resembles a comet in some ways, including a highly-eccentric orbit ($e \sim 0.89$) and a strong associated meteor shower (the Geminids). Yet this object has never been observed to exhibit any cometary activity, i.e., gas production. We observed 3200 Phaethon with the Caltech Submillimeter Observatory on two occasions, once while it was near its closest approach to Earth as it neared perihelion, and another while it was further from Earth post-perihelion. Observations of the $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$ rotational transitions of ^{12}CO, typically strong lines in comets and indicative of gas production, yielded no detection. Upper limits on the ^{12}CO production of 1.8×10^{28} and 7.6×10^{28} molecules s^{-1} for Phaethon were determined on these two occasions.

Keywords: Asteroids; Comets; Radio observations

1. Introduction

Asteroid 3200 Phaethon was discovered by the Infrared Astronomical Satellite in 1983 (Green and Kowal, 1983). Almost immediately thereafter its orbit was noted to be very similar to that of the Geminid meteor shower (Whipple, 1983). This makes it the only asteroid linked to a strong meteor shower. A possible exception is Asteroid 2003 EH1, which is associated with the Quadrantid shower (Jenniskens, 2004; Williams et al., 2004; Wiegert and Brown, 2005) but which has not yet been observed near perihelion and thus whether it is asteroidal or cometary in nature remains unclear.

The link between Phaethon and the Geminid meteor shower is based on the closeness of their orbits, thus one could argue that they are simply aligned by coincidence. However, based on the very small difference between their orbits (see Table 1) and the absence of other objects on orbits nearby, Wiegert and Brown (2004) determined that probability of the orbital similarity of Phaethon and the Geminids being due to a chance alignment is less than one in a thousand. Though Phaethon's current activity (if any) is certainly low, intermittent or both, a study of the orbits of observed Geminids has indicated that they are consistent with cometary release no more than 2000 years ago and possibly within the last 600 years (Gustafson, 1989). Thus ongoing, perhaps sporadic, gas production by this object remains a possibility.

If 3200 Phaethon is not a comet, this does not mean it cannot be the parent body of the Geminids. A collision or impact might have released the material which formed the Geminid stream. A new rare population of "main-belt comets" has been uncovered in the last several years (Hsieh and Jewitt, 2006), bodies whose gas and dust production may be partly the result of collisions. However, the sublimation of volatiles from the body's surface also has a role to play, as evidenced by the seasonal cycle of activity that has been seen in one of them (133P/Elst–Pizarro) to date (Hsieh et al., 2007).

Table 1
Standard orbital elements of 3200 Phaethon (NeoDys website http://newton.dm.unipi.it/cgi-bin/neodys/neoibo) and the Geminid meteor shower (Cook, 1973)

	a (AU)	e	q (AU)	i (deg)	Ω (deg)	ω (deg)	T_J
3200 Phaethon	1.27	0.890	0.140	22.2	265.4	322.0	4.51
Geminids	1.36	0.896	0.142	23.6	261.0	324.3	4.23

We note that Geminid meteors are much more durable than typical cometary meteors: studies of their ablation in Earth's atmosphere have shown that they have mean densities of 2.9 g cm^{-3} (Babadzhanov, 2002), the highest of any of the streams measured. This may imply that the Geminids are made of relatively strong rocky asteroidal material rather than more porous and fragile cometary material. However, the question is complicated by the small (0.14 AU; Cook, 1973) perihelion distance of the Geminid stream. Smaller than is typical of comets, this low perihelion distance could result in extreme baking and sintering of the meteoroid particles, producing more durable meteoroids than might otherwise be expected of a cometary meteoroid stream.

Phaethon's association with a strong meteor shower and its highly eccentric orbit ($e \approx 0.89$) make it a candidate cometary object. Yet in the over two decades since its discovery (which include many perihelion passages of its 1.43-year orbit), no cometary activity has ever been observed (Cochran and Barker, 1984; Chamberlin et al., 1996; Hsieh and Jewitt, 2005).

Phaethon's spectral type is B (Green et al., 1985), a primitive type associated with the outer portion of the main asteroid belt, though its albedo (0.11–0.17) is somewhat higher than would be expected of such a type (Veeder

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et al., 1984; Green et al., 1985), as was pointed out by Weissman et al. (2002). Visible and near IR spectroscopy of Phaethon support its identification as an asteroid rather than a comet nucleus (Licandro et al., 2007). Phaethon has been also linked with the smaller Asteroid 2005 UD, with which it shares a bluish color, an absence of dust production (Jewitt and Hsieh, 2006) and an orbital similarity (Ohtsuka et al., 2006). Is Phaethon then an asteroid, and if so, how did it produce its meteor stream?

The question of the nature of this unusual object can only be answered by ongoing observations. In particular, observations which might reveal gas production by this body are the most important to undertake, as a positive detection would unequivocally identify this object as a comet, though its muted activity might imply it was extinct or dormant. Given the lack of previous detections of gas from Phaethon, its gas production rate is undoubtedly low, and observations should ideally be conducted near perihelion, or as close to it as can be managed given the interfering presence of the Sun.

In this paper we describe our attempts to measure gas production on Phaethon through the detection of $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$ rotational transitions of the ^{12}CO molecule at the Caltech Submillimeter Observatory (CSO), located atop Mauna Kea, Hawaii. Observations in the mm/sub-mm range suffer the constraints of bad weather even more than traditional optical astronomy. This project arose from an idea to use time on the CSO that was unsuitable for projects requiring excellent atmospheric conditions for other purposes. The choice of Phaethon as a target, despite its lack of observed activity, was motivated by its meteor stream and the intermittency of activity seen in other comets e.g., in the main-belt: ongoing monitoring of this object seems justifiable. The $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$ rotational transitions of carbon monoxide (CO) are strong in bright comets, though not perhaps ideal indicators of gas production for Phaethon. They were chosen as being among our best bets given our observational window during mediocre conditions ($\tau_{225\ \mathrm{GHz}} \sim 0.15$). In fact our upper limit on gas production using these lines is comparable to that of a moderate-activity comet, and by observing as close to perihelion as possible, we hoped to catch Phaethon in outburst. Though our attempt was unsuccessful, only by ongoing observations will Phaethon's nature be clarified.

We present the three spectra we obtained from corresponding sets of observations and discuss our results in the next sections.

2. Observations

The three sets of observations were taken at the Caltech Submillimeter Observatory, with the 200–300 GHz receiver on 5 November 2004 and 13 September 2005 for the ^{12}CO ($J = 2 \rightarrow 1$) transition, and with the 300–400 GHz receiver on 5 November 2004 for the ^{12}CO ($J = 3 \rightarrow 2$) transition. All spectra were obtained with the high-resolution Acousto-Optic Spectrometer (AOS) of 50 MHz total bandwidth and approximately 100 kHz resolution. The CSO has a 10.4-m dish and a beam diameter of approximately 30 and 20 arcseconds at the frequencies in question (i.e., approximately 230 and 345 GHz for ^{12}CO $J = 2 \rightarrow 1$ and $J = 3 \rightarrow 2$, respectively). For all of our observations, the data were taken using the beam switching mode (i.e., by wobbling the secondary mirror) to allow for cancellation of sky background emission. While reducing the data we have set the receiver efficiencies to 70% for both transitions. This corresponds to situations where not only the main beam of the telescope probes the source, but also the sidelobes. This technique has been used by other investigators observing cometary lines at the CSO (e.g., Bockelée-Morvan et al., 2000). We assume that this would be applicable to our observations if there were a gas cloud surrounding 3200 Phaethon from which the sought transitions were detected (see Section 3 below).

For the observations obtained on 5 November 2004, 3200 Phaethon was 1.05 AU from Earth, allowing us a close look at the object as it passed, and 1.894 AU from the Sun, approaching perihelion. Its elevation angle varied from 54° to 28° in the morning sky, as it was moving rapidly towards the Sun. We obtained 50 min of observation (ON-source), but the $J = 2 \rightarrow 1$ rotational transition line from ^{12}CO was not detected. Given mediocre sky conditions ($\tau_{225\ \mathrm{GHz}} \simeq 0.15$) and a system temperature of $T_{\mathrm{sys}} \simeq 444$ K, we were able to integrate down to a noise floor of 14 mK (with a velocity resolution of $\simeq 1\ \mathrm{km\,s^{-1}}$ after "smoothing" the spectrum to lower the noise level), and determine an upper limit (3σ) of approximately $T \simeq 42$ mK for the brightness temperature of the line. We also attempted to detect the $J = 3 \rightarrow 2$ transition from ^{12}CO previously on the same night, when Phaethon was at an elevation of 70° to 59° with a similar outcome. For these observations, with a system temperature $T_{\mathrm{sys}} \simeq 918$ K, the 48 min of ON-source integration yielded an upper limit of $T \simeq 69$ mK in a velocity resolution of $\simeq 0.7\ \mathrm{km\,s^{-1}}$. Our last set of data was obtained on 13 September 2005 when we again attempted to observe the $J = 2 \rightarrow 1$ transition from ^{12}CO under comparable observing conditions (i.e., $\tau_{225\ \mathrm{GHz}} \simeq 0.16$ and $T_{\mathrm{sys}} \simeq 440$ K). On that night, 3200 Phaethon was 1.904 AU from Earth and 2.298 AU from the Sun approaching aphelion. Earlier observations nearer perihelion were impossible because Phaethon had been in the daytime sky for many months. This new set of data (50 min of integration ON-source), obtained at elevation angles ranging from 35° to 70°, yielded no detection and an upper limit of approximately $T \simeq 48$ mK, again with a velocity resolution of $\simeq 1\ \mathrm{km\,s^{-1}}$. The spectra that resulted from our observations are presented in Fig. 1.

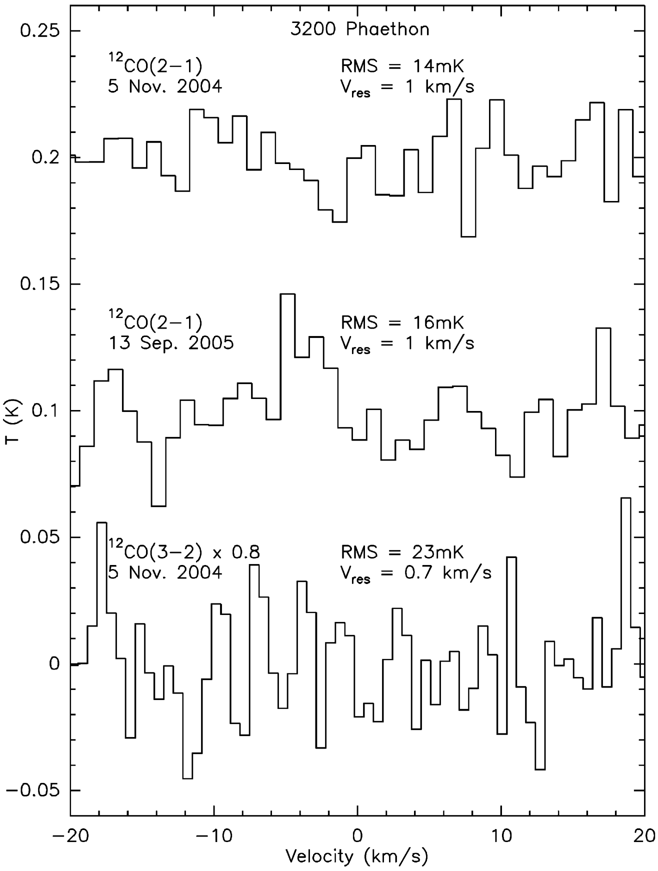

Fig. 1. The three spectra that resulted from our observations. The top two are for our attempts at a detection of the $J = 2 \rightarrow 1$ transition of ^{12}CO, while the bottom spectrum corresponds to our $J = 3 \rightarrow 2$ observations.

3. Discussion

The submillimeter rotational transitions of ^{12}CO have been studied in detail for comets and the strength of the lines can be linked to gas production rates (Crovisier and Le Bourlot, 1983).

Assuming a lifetime of ^{12}CO against dissociation by solar UV radiation at 1 AU of $\tau = 1.5 \times 10^6$ s [Huebner and Carpenter (1979) from Crovisier and Le Bourlot (1983)] and assuming a gas expansion velocity $v_{\mathrm{exp}} = 800\ \mathrm{m^{-1}\,s}$ (the pre-perihelion value determined for Hyakutake from submillimeter observations by Biver et al., 1999), any ^{12}CO cloud around 3200 Phaethon should have a diameter $\sim 2.4 \times 10^6$ km, with an angular size of about 0.9° at 1 AU. A comparison of this angular size with the CSO main beam sizes quoted earlier for our observations justifies the efficiency adopted for our observations (i.e., 70%).

Assuming fluorescence equilibrium and a Haser distribution (Haser, 1957; Bertaux et al., 1998) with $\gamma_{\mathrm{CO}} = v_{\mathrm{exp}}\tau = 1.2 \times 10^6$ km, and using an emission constant $T_B \Delta v / \langle N_{\mathrm{CO}} \rangle$ of 3.65×10^{-16} K km s^{-1} (molecules cm^{-2})$^{-1}$ and 8.08×10^{-16} K km s^{-1} (molecules cm^{-2})$^{-1}$ for the $J = 2 \to 1$ and $J = 3 \to 2$ transitions, respectively (Crovisier and Le Bourlot, 1983), we can derive a corresponding upper limit on Q_{CO}, the rate of ^{12}CO production, of approximately 1.8×10^{28} molecules s^{-1} for 5 November 2004 (from the $J = 3 \to 2$ transition). More precisely, at 1.05 AU (the distance between Earth and 3200 Phaethon during the corresponding observations) the dependence on the measured and assumed parameters can be expressed as

$$Q_{\mathrm{CO}} \approx 3.60 \times 10^{28} \left(\frac{v_{\mathrm{exp}}}{800\ \mathrm{m\,s^{-1}}} \right)^2 \left(\frac{T_B}{42\ \mathrm{mK}} \right) \mathrm{molecules\,s^{-1}} \tag{1}$$

for the $J = 2 \to 1$ transition, and

$$Q_{\mathrm{CO}} \approx 1.77 \times 10^{28} \left(\frac{v_{\mathrm{exp}}}{800\ \mathrm{m\,s^{-1}}} \right)^2 \left(\frac{T_B}{69\ \mathrm{mK}} \right) \mathrm{molecules\,s^{-1}} \tag{2}$$

for the $J = 3 \to 2$ transition. Using an equation similar to Eq. (1) for a distance of 1.904 AU we also establish an upper limit of $Q_{\mathrm{CO}} \approx 7.6 \times 10^{28}$ molecules s^{-1} for 13 September 2005.

These upper limits are lower than production rates observed for very bright comets at the same heliocentric distance, e.g., C/1995 O1 (Hale–Bopp), $Q_{\mathrm{CO}} = 2.07 \times 10^{30}$ molecules s^{-1} (DiSanti et al., 2001). The limits are comparable to the production rate of C/1996 B2 Hyakutake, $Q_{\mathrm{CO}} \approx 5 \times 10^{28}$ molecules s^{-1} near 1 AU (Biver et al., 1999), though it is a long-period comet and expected to be rich in ices.

Comet 2P/Encke, an old low-activity comet, might provide a better benchmark. Though its carbon monoxide production has not been measured to our knowledge, we can estimate this from its H_2O production rate, which has measured at 0.8 to 2.6×10^{28} molecules s^{-1} at similar heliocentric distances (Mäkinen et al., 2001). The ^{12}CO to H_2O ratio in comets is variable, ranging from 0.5 to 22% (Biver et al., 1999; DiSanti et al., 2001, 2002, 2003, 2007; Mumma et al., 2001a, 2001b, 2001c; Feldman et al., 2002). Taking the ratio to be 5%, we can derive a corresponding expected ^{12}CO production rate of 0.4×10^{27} to 1.3×10^{27} molecules s^{-1} for Comet Encke. Though a nearly-extinct comet could produce ^{12}CO at even lower rates, this presents us with a target measurement sensitivity of $Q_{\mathrm{CO}} \sim 10^{27}$ molecules s^{-1}.

In view of these numbers it will be necessary to make deeper observations of 3200 Phaethon in order to detect any ^{12}CO production or to reduce significantly our derived upper limits. It follows that we need to increase our sensitivity by at least an order of magnitude. The results discussed here were obtained under relatively poor sky conditions and improving these limits should be feasible with a combination of longer exposure times and better observing conditions (e.g., $\tau_{225\ \mathrm{GHz}} \simeq 0.05$), as is relatively common (20 to 25% of the time) on Mauna Kea. The sensitivity can also be increased by observing Phaethon when it is closest to Earth, as the detection limit drops approximately linearly with the Earth–comet distance. Observations of this object during its upcoming close approach to Earth ($\lesssim$0.13 AU in December 2007) would thus be particularly recommended.

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