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DETERMINATION OF AN UPPER LIMIT FOR THE WATER OUTGASSING RATE OF MAIN-BELT COMET P/2012 T1 (PANSTARRS)*

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ABSTRACT

A new Main-Belt Comet (MBC) P/2012 T1 (PANSTARRS) was discovered on 2012 October 6, approximately one month after its perihelion, by the Pan-STARRS1 survey based in Hawaii. It displayed cometary activity upon its discovery with one hypothesis being that the activity was driven by sublimation of ices; as a result, we searched for emission assumed to be driven by the sublimation of subsurface ices. Our search was of the H₂O 1₁₀–1₀₁ ground state rotational line at 557 GHz from P/2012 T1 (PANSTARRS) with the Heterodyne Instrument for the Far Infrared on board the *Herschel Space Observatory* on 2013 January 16, when the object was at a heliocentric distance of 2.504 AU and a geocentric distance of 2.064 AU. Perihelion was in early 2012 September at a distance of 2.411 AU. While no H₂O line emission was detected in our observations, we were able to derive sensitive 3 σ upper limits for the water production rate and column density of $<7.63 \times 10^{25}$ molecules s^{−1} and of $<1.61 \times 10^{11}$ cm^{−2}, respectively. An observation taken on 2013 January 15 using the Very Large Telescope found the MBC to be active during the *Herschel* observation, suggesting that any ongoing sublimation due to subsurface ice was lower than our upper limit.

Key words: comets: individual (P/2012 T1 PANSTARRS) – minor planets, asteroids: individual (P/2012 T1 PANSTARRS)

Online-only material: color figure

1. INTRODUCTION

Recent observational and theoretical developments have suggested that the objects between Mars and Jupiter in the Main Asteroid Belt hold considerably more water ice than traditionally thought—as distinct from the widespread observation of hydrated minerals in asteroids (e.g., Rivkin et al. 2002; Vilas & Gaffey 1989). They would hold this water ice despite being in orbits that are presumably stable over the lifetime of the solar system and thus having surfaces that have received significant solar energy input. For example, the snow line at the time of planet formation could have been close to Mars’ orbit (Sasselov & Lecar 2000; Lecar et al. 2006); subsurface ice in asteroids can survive for the age of the solar system if buried under a dusty surface (Schorghofer 2008); surface ice has possibly been detected on the large main-belt asteroid (24) Themis (Rivkin & Emery 2010; Campins et al. 2010).

Further evidence for significant water in the Main Belt comes from the so-called Main-Belt Comets (MBCs; Hsieh & Jewitt 2006; Bertini 2011; Jewitt 2012). These objects show cometary activity, and that cometary activity appears to be sustained rather than impulsive. The MBCs have orbits squarely within the Main Belt, and their orbits are found to be stable; as such, the objects are considered likely to be native to their current residence regions in the Main Belt. Thus, the implication is that volatile material incorporated into these bodies when they

formed has survived to the present day. This also means that MBCs have the potential to place observational constraints on the temperature and compositional structure of the early solar system and our protoplanetary disk, giving insight into the solar system’s formation.

In a recent study (Waszczak et al. 2013) of the Palomar Transient Factory survey database, upper limits on the possible population size of active MBCs were derived at a 2 σ level of 22 active MBCs (per million main-belt asteroids down to 1 km diameter). We note that of the 10 known Main Belt objects observed to have shown extended emission from dust, we consider 7 of them to be MBCs (i.e., excluding P/2010 A2, P/2012 F5, and (596) Scheila), apparently having sustained activity due to sublimation of ices as the more traditional comets do. P/2012 T1, the object considered here, would be the seventh MBC.

The MBC P/2012 T1 (PANSTARRS) was discovered on October 6 by the 1.8 m Pan-STARRS1 (PS1) survey telescope on Haleakala with follow-up images confirming the object to be cometary in nature with a 10′–15′-long tail (Wainscoat et al. 2012). Observation campaigns performed by various ground-based observatories (Keck 10 m, the University of Hawaii 2.2 m, 6.5 m Baade, 6.5 m Clay Magellan, 1.8 m Perkins, etc.; Hsieh et al. 2013) found the object’s intrinsic brightness roughly doubling from the time of its discovery until mid-November, after which it was then seen to decrease by $\approx 60\%$ from late December to early February. Similar long-lived photometric behavior has been observed for several other MBCs, suggesting that the activity of P/2012 T1, deemed to

* *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

Figure 1. Averaged spectra of the two orthogonal polarizations of the H_2O line $1_{10}-1_{01}$ at 556.936 GHz toward the MBC P/2012 T1 (PANSTARRS) obtained by *Herschel*/HIFI on UT 2013 January 16.31 with the WBS (thick blue line) and HRS (thin red line) spectrometers. The HRS spectrum have been resampled to a 480 kHz resolution per channel with a rectangular window function. The vertical axis is the calibrated main beam brightness temperature and the horizontal axis is the cometocentric Doppler velocity.

(A color version of this figure is available in the online journal.)

belong to the Lixiaohua asteroid family, could likewise be driven by sublimation (Hsieh et al. 2012a, 2012b, 2013).

While sublimation of water ice in main-belt objects is strongly implied by MBC activity, gas has never been directly observed via spectroscopy, though attempts have been made (Jewitt et al. 2009; Hsieh et al. 2012b, 2012c, 2013; de Val-Borro et al. 2012a). Given the difficulty of detecting weak, distant, and transient gas emission, these non-detections do not rule out the presence of gas, however. A bright and actively sublimating MBC offers the unique opportunity to confirm the presence of sublimating volatile material in a main-belt object, and thus confirm the plausibility of ice in all of the other MBCs. This would strongly validate the potential that MBCs are believed to have for tracing the volatile content of the inner solar system. The Heterodyne Instrument for the Far Infrared (HIFI; de Graauw et al. 2010) on board the ESA *Herschel Space Observatory* (Pilbratt et al. 2010) proves to be the most sensitive instrument for directly observing water in a distant comet (e.g., Bockelée-Morvan et al. 2010). The HIFI instrument provides very high-resolution spectroscopy that can resolve the line shape and enable the determination of accurate production rates (e.g., Hartogh et al. 2010).

In this Letter, we present the *Herschel* DDT (Director Discretionary Time) observation of the $1_{10}-1_{01}$ fundamental rotational transition of H_2O at 557 GHz in P/2012 T1. This observation was requested to be performed on 2013 January 16, at the opening of the *Herschel* visibility window for the target, when the MBC was deemed to be still active; this was confirmed via our DDT observations using the VLT FORS2 instrument (Appenzeller et al. 1998) performed on January 15. The *Herschel* observation was intended to test the prediction that the observed cometary activity of MBCs is driven by sublimation of water ices and to constrain the production process.

2. OBSERVATIONS

On the basis of its obvious and ongoing activity following its perihelion passage in early 2012 September, the MBC P/2012 T1 was observed by *Herschel* on UT 2013 January 16.31

with a total on-target integration time of 4.8 hr, when it was at an approximate heliocentric distance of 2.504 AU, a distance of 2.064 AU from the satellite (*Herschel* ObsID 1342259756), and at a phase angle of $22^\circ 55'$. The object was tracked using an up-to-date ephemeris provided by the JPL Horizons system.

The line emission from the fundamental *ortho*- H_2O $1_{10}-1_{01}$ line at 556.936 GHz was searched for in the upper sideband of the HIFI band 1a mixer. The observation was performed in the frequency-switching observing mode with a frequency throw of 94.5 MHz, using both the wide-band spectrometer (WBS) and the high-resolution spectrometer (HRS). In this observing mode there is no need to observe a reference position on the sky and the on-target integration time is maximized. However, the statistical noise may be underestimated for observations in frequency-switched mode owing to uncertainties in baseline removal (Bockelée-Morvan et al. 2012).

In addition to the *Herschel* observations, three 300 s V-band VLT FORS2 images were taken around 01:00 UT on 2013 January 15, with the telescope tracking the comet's motion. At this time the comet was at 2.502 AU from the Sun, 2.052 AU from Earth, and at a phase angle of $22^\circ 26'$.

3. DATA ANALYSIS

In the case of the HIFI data set, the standard HIFI processing pipeline v9.2 (belonging to the *Herschel* interactive processing environment software package; Ott 2010) was used to reduce the data to calibrated level 2 data products.

The spectral resolution of the WBS is 1 MHz (0.54 km s^{-1} at the frequency of the observed line), while the HRS was used in its high-resolution mode with a resolution of 120 kHz (0.065 km s^{-1}). The main beam brightness temperature scale was computed using a beam efficiency of 0.75 and a forward efficiency of 0.96. The folded spectrum was obtained by averaging the original spectrum with a shifted and inverted copy. Horizontal and vertical polarizations were averaged, weighted by the root mean square amplitude, to increase the signal-to-noise ratio. The pointing offset of horizontal and vertical polarization spectra is $6''.6$ in band 1a, which, at the observed frequency, is approximately 20% of the half-power beam width.

The frequency switching observing mode introduces quite a strong baseline ripple that can be removed by performing a least-squares fit of a linear combination of sine waves. We applied the Lomb-Scargle periodogram method (initially proposed by Lomb 1976, and additionally developed by Scargle 1982) to the HRS and WBS spectra and fitted the baseline ripple using the strongest peaks in the frequency spectrum. The reduction methods applied for baseline removal and denoising of the *Herschel*/HIFI data are described in greater detail in de Val-Borro et al. (2012b). We show the averaged spectra of the two orthogonal polarizations in the HRS and WBS spectra in Figure 1.

In the case of the three VLT FORS2 V band images, the first image was affected by a cosmic ray near to the comet, but the sum of the remaining frames is shown in Figure 2. The comet was clearly active at that time, approximately one day before the *Herschel* observations. The seeing, measured using the FWHM of the star trails in this image, was around $0''.8$ and conditions were photometric. Photometry was performed with an aperture of radius $3''.06$ to avoid contamination from the nearby trailed star. The magnitude within this aperture is $m_V = 21.47 \pm 0.01$, corresponding to a reduced magnitude of $V(1,1,0) = 17.47$, assuming a phase function of $0.02 \text{ mag deg}^{-1}$, appropriate for cometary dust (Meech & Jewitt 1987). The corresponding

Figure 2. Context broad band image of the MBC on the 2013 January 15 using the VLT FORS2 detector.

$Af\rho$ value (A'Hearn et al. 1989) is 2.7 cm (not including any phase angle correction), with the $\rho = 3''.06$ aperture radius corresponding to 4560 km at the distance of the comet.

The slope of the radial profile is -1.6 , slightly steeper than expected for a steady-state coma under the influence of radiation pressure (Jewitt & Meech 1987), which means that $Af\rho$ is not independent of the choice of ρ in this case. We can say that it is very low, implying a weakly active comet. This low value is comparable with what has been provided by Hsieh et al. (2013) on this target for the January timeframe. The photometry also allows us to place an upper limit on the size of the nucleus: We obtain $r < 1.3$ km, assuming typical comet nucleus values for the geometric albedo (4%) and phase function ($0.04 \text{ mag deg}^{-1}$).

4. OUTGASSING RATE UPPER LIMIT

Upon analyzing our data, we found no detection of H_2O , although with the fact that it was shown to be still active at the time of our observation, we expected the dust emission activity to be driven by the sublimation of subsurface material.

We used a molecular excitation model to calculate the population of the rotational levels of water as a function of nucleocentric distance as well as to derive the production rates. The model in use is based upon the publicly available accelerated Monte Carlo radiative transfer code *ratran* (Hogerheijde & van der Tak 2000). To derive the production rates, the code includes collisional effects as well as infrared fluorescence by solar radiation. We used the one-dimensional spherically symmetric version of the code as described in Bensch & Bergin (2004). This same version has been utilized to analyze both *Herschel* and ground-based cometary observations (Hartogh et al. 2010, 2011; de Val-Borro et al. 2010, 2012a, 2012b).

Input parameters to this model include the electron density, gas kinetic temperature, expansion velocity, and the radial gas density profile.

Electron density and gas kinetic temperature profile values extracted from (Biver et al. 1997; de Val-Borro et al. 2010) were fed into the model. For the case of the kinetic temperature (used to control the molecular excitation in the collisional region), a

Table 1
 H_2O Production Rate ($Q_{\text{H}_2\text{O}}$) and Column Density (N_{col})
Derived for Different Gas Kinetic Temperatures

Temperature (K)	$Q_{\text{H}_2\text{O}}$ (molecules s^{-1})	N_{col} (cm^{-2})
10	$< 8.0 \times 10^{25}$	$< 1.68 \times 10^{11}$
15	$< 7.6 \times 10^{25}$	$< 1.60 \times 10^{11}$
20	$< 7.3 \times 10^{25}$	$< 1.54 \times 10^{11}$
Mean	$< 7.63 \times 10^{25}$	$< 1.61 \times 10^{11}$

Notes. Assuming a line area upper limit of 3.6 mK km s^{-1} $T_{\text{MB}} dv$ at 3σ , with the following excitation parameters $r_h = 2.504 \text{ AU}$, $\Delta = 2.064 \text{ AU}$, $v_{\text{exp}} = 0.5 \text{ km s}^{-1}$, $x_{\text{ne}} = 0.2$, pointing offset = $3''.5$ (if the comet was in between the two band 1A beams), one can obtain the following H_2O production rates and associated column densities for P/2012 T1, at different gas temperatures. Note that if a $v_{\text{exp}} = 0.4 \text{ km s}^{-1}$ is used, this would lower the $Q_{\text{H}_2\text{O}}$ by 15%.

range of values from 10 to 20 K was input. Since the electron density in the coma is not well constrained, an electron density scaling factor of $x_{\text{ne}} = 0.2$ with respect to the standard profile derived from observations of comet 1P/Halley has been used (e.g., Hartogh et al. 2010).

The expansion velocity (assumed constant in the coma), and the radial gas density profile for water was obtained based upon a standard spherically symmetric Haser distribution. For lower-activity comets, and in this case P/2012 T1, an expansion velocity of 0.5 km s^{-1} has been used (Tseng et al. 2007; Biver et al. 2007). While Tseng et al. (2007) are limited by measurements taken for $Q_{\text{OH}} < 10^{28}$ at r_h distances $> 2 \text{ AU}$, the Biver et al. (2007) paper gives the $\text{FWHM} = 0.95 \text{ km s}^{-1}$ for the comet C/2003 K4 (LINEAR) water line at 2.2 AU from the Sun, which can be interpreted as $v_{\text{exp}} = 0.5 \text{ km s}^{-1}$, taking into account the fact that self-absorption makes the line a little narrower. Finally, from the temperature expected at the subsolar point where ice sublimates, we derived a thermal velocity of 0.35 km s^{-1} .

For the line area upper limit, based upon removal of sine baselines, with smoothing of approximately 25% and computed on a $[-0.7 \text{ } 0.7 \text{ km s}^{-1}]$ window, we derive a $1\sigma \int T_{\text{MB}} dv$ value of $1.63 \text{ mK km s}^{-1}$ from the HRS spectrum and $0.88 \text{ mK km s}^{-1}$ from the WBS spectrum.

Taking an upper limit of $3.6 \text{ mK km s}^{-1} \int T_{\text{MB}} dv$ at 3σ from the mean of the HRS and WBS values, we can obtain upper limits for the water production rate (Q) at different temperature ranges.

With this line area upper limit, using expansion velocity characteristic of weak comets (0.5 km s^{-1}), a gas kinetic temperature of 20 K, we derive a sensitive 3σ upper limit of $Q < 7.3 \times 10^{25} \text{ molecules s}^{-1}$ from the WBS and HRS data (see Table 1). An upper limit of $< 7.63 \times 10^{25} \text{ molecules s}^{-1}$ is derived from the mean of the WBS and HRS upper limits for a gas expansion velocity of 0.5 km s^{-1} and gas kinetic temperatures of 10, 15, and 20 K.

5. DISCUSSION AND CONCLUSIONS

With the *Herschel* capability to directly detect H_2O in MBCs, it is important to stress the key relevance of such results to the knowledge of water production on these bodies.

In addition to the current work, this capability for direct measurements on MBCs has been demonstrated when MBC

176P/LINEAR was observed using *Herschel*/HIFI in 2011 August, about one month post-perihelion. In that case, no water line emission was detected and a 3σ upper limit was obtained on the production rate of $<4 \times 10^{25}$ molecules s^{-1} (de Val-Borro et al. 2012b).

Besides a direct detection, other means exist to derive water production rates although they are limited in nature and primarily model-dependent. We will look at two of these briefly for comparative purposes.

One particular way to derive H_2O production is via the search for CN. Searches for CN (and thus deriving a water production rate via a log based ratio linking Q_{CN} and Q_{OH} in “typical” comets) have taken place with four of the other MBCs, all of which were unsuccessful. For those MBCs, estimated water production rates of $Q < 10^{26}$ molecules s^{-1} were proposed using a $Q_{\text{CN}}/Q_{\text{OH}}$ mixing ratio of 10^{-3} . For P/2012 T1, Hsieh et al. (2013) report that CN was also not detected but an estimate of the expected H_2O upper limit of $Q < 5 \times 10^{25}$ molecules s^{-1} based upon an average ratio for other comets has been made.

One can also derive a value for the production rate via the $Af\rho$ measurement using visible light observations to estimate the coma brightness of a typical Jupiter Family Comet. The visible light proxy for dust production is the quantity $Af\rho$, where A is the bond albedo of the dust, f is the dust area filling factor in the field-of-view, and ρ is the projected radius of the field-of-view, typically expressed in units of cm (A'Hearn et al. 1984). For comae with constant isotropic outflows, $Af\rho$ is independent of aperture size. With our FORS2 observation, a corresponding $Af\rho$ value (A'Hearn et al. 1989) of 2.7 cm (not including any phase angle correction) has been estimated. Assuming a first order approximation, where $Af\rho$ in cm is found to be roughly equal to the dust production rate in kg s^{-1} (A'Hearn et al. 1995), we find 2.7 kg s^{-1} of $\text{H}_2\text{O} = 9 \times 10^{25}$ molecules s^{-1} . Separate to this, we note that the photometry from our FORS2 observation also allowed us to place an upper limit on the radius of the nucleus which we estimate to be <1.3 km, assuming typical comet nucleus values for the geometric albedo (4%) and phase function ($0.04 \text{ mag deg}^{-1}$).

The goal of the *Herschel* DDT observation was to detect H_2O in a clearly active MBC, assumed to be produced from sublimating subsurface ices. Besides sublimation of subsurface ices, other mechanisms have been proposed to drive mass loss from small bodies, including rotational instability, impact ejection and thermal fracture (see Jewitt 2012 for a recent review of mass loss mechanisms in MBCs). A study performed on this comet by Hsieh et al. (2013) for these different possibilities concluded that sublimation is indeed considered the key behind the observed activity.

Although the goal conditions of observing an active MBC were met, with our VLT FORS2 observation clearly showing activity and ground-based observations since that date confirming that the activity continued until the end of 2013 February (Moreno et al. 2013), we were, in the end, unsuccessful in achieving that goal as no detection of H_2O was made.

However, based upon our analysis above, and recognizing that: (1) the activity of the MBC observed at the time of the *Herschel* observation was already less than what was observed in the preceding months (Hsieh et al. 2013); (2) *Herschel* did not detect water but the measurement was successful in providing a sensitive 3σ upper limit; (3) the upper limits derived from less direct methods (Hsieh et al. 2013), e.g., $Af\rho$ measurements, provide values equivalent and comparable to our

direct measurement (thus effectively supporting the strategies being used in such cases, where no direct measurements are available), we conclude that if the activity was due to sublimation of subsurface water ice, the water production rate at the time of our observations was lower than $<7.63 \times 10^{25}$ molecules s^{-1} for MBC P/2012 T1 (PANSTARRS).

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