Icarus 264 (2016) 48–61

Contents lists available at ScienceDirect

Icarus

journal homepage: www.journals.elsevier.com/icarus

When comets get old: A synthesis of comet and meteor observations of the low activity comet 209P/LINEAR

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ARTICLE INFO

Article history:
Received 20 June 2015
Revised 24 August 2015
Accepted 1 September 2015
Available online 15 September 2015

Keywords:
Meteors
Comets, dust
Comets, dynamics
Comets, nucleus
Near-Earth objects

ABSTRACT

It is speculated that some weakly active comets may be transitional objects between active and dormant comets. These objects are at a unique stage of the evolution of cometary nuclei, as they are still identifiable as active comets, in contrast to inactive comets that are observationally indistinguishable from low albedo asteroids. In this paper, we present a synthesis of comet and meteor observations of Jupiter-family Comet 209P/LINEAR, one of the most weakly active comets recorded to-date. Images taken by the Xingming 0.35-m telescope and the Gemini Flamingo-2 camera are modeled by a Monte Carlo dust model, which yields a low dust ejection speed (1/10 of that of moderately active comets), dominance of large dust grains, and a low dust production of 0.4 kg s^{-1} at 19 d after the 2014 perihelion passage. We also find a reddish nucleus of 209P/LINEAR that is similar to D-type asteroids and most Trojan asteroids. Meteor observations with the Canadian Meteor Orbit Radar (CMOR), coupled with meteoroid stream modeling, suggest a low dust production of the parent over the past few hundred orbits, although there are hints of a some temporary increase in activity in the 18th century. Dynamical simulations indicate 209P/LINEAR may have resided in a stable near-Earth orbit for $\sim 10^4$ yr, which is significantly longer than typical JFCs. All these lines of evidence imply that 209P/LINEAR as an aging comet quietly exhausting its remaining near surface volatiles. We also compare 209P/LINEAR to other low activity comets, where evidence for a diversity of the origin of low activity is seen.

1. Introduction

Dormant comets are comets that have depleted their volatiles in the near surface layers but may still possess an ice-rich interior. It is not easy to study these objects directly, as their optical properties are indistinguishable from those of some of their asteroidal counterparts. Dormant comets among the population of near-Earth objects (NEOs) are particularly interesting, as they may have a significant contribution to Earth's history. It has been suggested $\sim 10\%$ of NEOs had their origins as Jupiter-family Comets or JFCs (e.g. Fernández et al., 2002; DeMeo and Binzel, 2008).

The dynamical lifetime of common JFCs is about 10^5 yr (Levison and Duncan, 1994). The physical lifetime of kilometer-sized JFCs, however, is estimated to be only a few 10^3 yr (e.g. Di Sisto et al., 2009). It is therefore evident that a typical JFC, presuming it does not fragment or split, would spend most of its time as a dormant comet. The details of the active-dormancy transition remain nebulous, but classical understanding of cometary evolution argues that the transition might include a period of low or intermittent cometary activity, possibly due to the buildup of dust mantles on the surface (c.f. Jewitt, 2004). Hence, it is natural to speculate that some weakly active comets may be active-dormancy transitional objects. From an observer's perspective, these objects are at a unique stage of the evolution of cometary nuclei, as they are still observationally identifiable as physical comets, as opposed to completely dormant comets that are indistinguishable from low albedo asteroids.

We define a low activity comet as a comet where the absolute total magnitude, M_1, is higher (fainter) than the absolute magnitude of a dark asteroid (defined by V-band geometric albedo $p_v = 0.1$) of equivalent effective body (nucleus) size. The physical implication of this definition is that the cometary activity is so low, that the comet would be recognized as a dark asteroid

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http://dx.doi.org/10.1016/j.icarus.2015.09.003

($p_v < 0.1$) if extended cometary features are unresolvable to an observer. Mathematically, the definition can be expressed as

$$M_1 > 16.6 - 5\log\left(\frac{R_N}{1\ \mathrm{km}}\right) \quad (1)$$

where R_N is the effective nucleus radius. Among the 121 comets with constrained nucleus sizes,[1] we find 9 comets meeting our definition of low activity comets (Table 1) of which 8 are near-Earth JFCs.

Table 1
A list of low activity comets according to the definition given in Section 1.

Comet	M_1	R_N (km)	Assoc. meteor shower
10P/Tempel 2	13.2	10.6[a]	–
28P/Neujmin 1	11.5	21.4[a]	–
102P/Shoemaker 1	15.7	1.6[b]	–
184P/Lovas 2	14.4	6.2[b]	–
209P/LINEAR	16.9	2.7[c]	Camelopardalids
252P/LINEAR	18.6	0.5[d]	Predicted, not yet observed[g]
289P/Blanpain	22.9	0.32[e]	Phoenicids
300P/Catalina	18.3	1.4[f]	June ϵ-Ophiuchids (?)
C/2001 OG108 (LONEOS)	13.1	13.6[a]	–

[a] Lamy et al. (223–264).
[b] Scotti (1994).
[c] Howell et al. (209).
[d] Drahus (2015, personal communication).
[e] Jewitt (2006).
[f] Harmon et al. (2006).
[g] Unpublished data from Maslov (http://feraj.narod.ru/Radiants/Predictions/252p-ids2016eng.html, retrieved 2015 May 2).

What are the nature and the origins of these comets? To answer this question, we need to look at their physical and dynamical properties. In particular, we note four of these comets – namely 209P/LINEAR, 252P/LINEAR, 289P/2003 WY25 (Blanpain) and 300P/2005 JQ5 (Catalina) – can produce meteor showers currently observable at Earth. Meteor showers are caused by cometary dusts ejected in past orbits of the parent, therefore meteor observations have the potential of enhancing our understanding of the physical history of the parent, as demonstrated in the investigation of the present and past activity of 55P/Tempel-Tuttle (e.g. Yeomans, 1981; Brown, 1999) and a couple of potential dormant comets (e.g. Babadzhanov et al., 2012; Kokhirova and Babadzhanov, 2015).

In this paper, we focus on one particular comet in our list, 209P/LINEAR. 209P/LINEAR is among the most weakly active comets ever recorded (e.g. Schleicher, 2014; Ishiguro et al., 2015) and is associated with a new meteor shower, the Camelopardalids (e.g. Jenniskens, 2014; Madiedo et al., 2014). What makes 209P/LINEAR ideal in studying cometary dormancy transition is (1) the close approach to the Earth of the comet during its 2014 perihelion passage, reaching ~ 0.05 AU from the Earth where it had brightened to $V \sim 11$ magnitude; and (2) the simultaneous encounter of a series of dust trails produced by the comet in its past orbits. These two events provide a rare opportunity to look at a potential comet-asteroid transitional object from two complementary approaches. Therefore, we observe 209P/LINEAR itself (Section 2) as well as the associated meteor activity (Section 3) to characterize the current state and recent history of the comet's activity. The observations are coupled with the results from numerical simulations to understand the nature and origin of 209P/LINEAR (Section 4). We also discuss the implication of our results to the state of to other low activity comets through the examination of 209P/LINEAR.

2. The comet

2.1. Observation

Imaging observations were conducted with three facilities at three different epochs. The observations and reduction procedures are summarized below and tabulated in Table 2.

1. Gemini North + Gemini Multi-Object Spectrographs (GMOS) camera at 2014 April 9.25 UT. This is a single frame taken as a snapshot observation. The observation was conducted relatively early in the active phase of 209P, making it suitable for examining the initial activation of the comet.
2. The 0.35-m telescope + QHY-9 camera at Xingming Observatory on 2014 May 18.75 UT. Around this date, the viewing geometry was favorable for separating dust of different sizes and emission epochs. The observation was conducted without filters and was processed using standard procedures (bias and dark frame subtraction, flat frame division).
3. Gemini South + Flamingo-2 (F-2) camera on 2014 May 25.94 UT. Around this date, the Earth was close to the comet and was near the orbital plane of the comet. The observation was conducted in the K_s band, with 15 s of exposure of each frame. The telescope was nodded in the direction perpendicular to the tail axis, to avoid contamination from the tail signal at the sky subtraction stage. As the comet was moving at a fast rate of ~ 18″/min (or 25 pix per frame), we opted for the non-guided non-sidereal tracking mode to avoid frequent changes of guide stars. Because of this, a small fraction (<5%) of frames suffer from poor tracking and are discarded. At the end, a total of 41 frames were useful for later analysis. The data reduction is performed with the Image Reduction and Analysis Facility (IRAF) supplied by Gemini.

2.2. Results and analysis

2.2.1. Start of cometary activity and general morphology

Previous researches (Hergenrother, 2014; Ishiguro et al., 2015) found that the activity of 209P/LINEAR started at a small activation distance of $r_H = 1.4$ AU. With the GMOS image, we conduct an independent check of the start time of activity of 209P/LINEAR. This is done by comparing the surface brightness profile to a synchrone model (Finson and Probstein, 1968). We estimate the start of activity occurred no later than late February 2014 or a lead time of $\tau \sim 50$ d, where 209P/LINEAR was at $r_H = 1.4$ AU (Fig. 1). This is in agreement with previous results.

Composite images taken by Xingming 0.35-m telescope and Gemini F-2 on May 18 and 25 are shown as Fig. 2. In the optical image from Xingming, 209P/LINEAR showed a symmetric coma measured 6—7″ (or about 50% larger than mean Full-Width-Half-Maximum or FWHM of background stars) in size and a mostly straight dust tail extended beyond the field of view. In the near infrared image from F-2, the nucleus, with the same FWHM compared to background stars, is clearly separated from the coma. The coma is significantly elongated along the Sun-comet axis, with the sunward side extending ~ 5″ or ~ 230 km towards the solar direction.

2.2.2. Modeling the dust

To understand the dust properties, we model the observations using a Monte Carlo dust model evolved from the one used in Ye and Hui (2014). The dynamics of the cometary dust are determined by two parameters: the ratio between radiation pressure and solar gravity, $\beta_{rp} = 5.7 \times 10^{-4}/(\rho_d a_d)$, where ρ_d the bulk density of the dust and a_d the diameter of the dust, both in SI units (Wyatt and Whipple, 1950; Burns et al., 1979); and the initial ejection velocity of the dust. The latter is found following the philosophy of the

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[1] The nucleus sizes of these 121 comets are extracted from the JPL Small-Body Database (http://ssd.jpl.nasa.gov/sbdb_query.cgi) on 2015 June 3.