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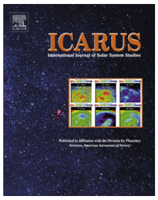

The established meteor showers as observed by CAMS

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ABSTRACT

Orbital elements are presented for 70 of the 95 meteor showers considered "established" by the International Astronomical Union. From 2010 October 21 until 2013 March 31, the low-light-video based *Cameras for Allsky Meteor Surveillance* project (CAMS) measured a total of 110,367 meteoroid trajectories and pre-atmospheric orbits from mostly −2 to +4 magnitude meteors with a precision of <2° (median 0.4°) in apparent radiant direction and <10% (median 0.9%) in speed. This paper discusses how the already established showers manifest in this data. Newly resolved components in the radiant distribution shed light on the dynamics and physical lifetime of parent bodies and their meteoroids. Many multi-component showers have associated parent bodies with nodal lines not much rotated from that of their meteoroids (Encke Complex, Machholz Complex, Phaethon Complex, and now also the 169P/NEAT Complex). These may result from a parent body disruption cascade, with the disruption-generated meteoroids fading on the short timescale of a few hundred to a few thousand years. In particular, the Northern and Southern Taurids of the Encke Complex are decomposed here into 19 individual streams. Seven of these streams can be paired with mostly sub-km sized potential parent body asteroids that move in 2P/Encke-like orbits that span the narrow semi-major axis range of 2.20–2.35 AU. The meteoroids in these Taurid streams do not survive long enough for the nodal line to fully rotate relative to that of their parent body.

1. Introduction

The International Astronomical Union's Working List of Meteor Showers[1] included 495 meteor showers at the end of March 2013, but only 95 "established" showers were certain to exist (Jenniskens et al., 2009; Williams, 2011; Jopek and Kanuchová, 2014). Each established shower is evidence of past activity of a parent comet or asteroid, tracing its mass loss and dynamics. Many parent bodies are only now being discovered by the ongoing Near-Earth Object surveys (Jenniskens, 2006). A good understanding of the meteoroid streams at Earth fuels planetary science and planetary defense studies and is essential for satellite impact hazard mitigation.

The *Cameras for Allsky Meteor Surveillance* (CAMS) project was conceived to validate as many as possible of the 400 unconfirmed showers (Jenniskens et al., 2011a). To achieve that goal, CAMS scaled up existing techniques for measuring meteoroid trajectories from multi-station video imaging of meteors (Clifton, 1973; Hawkes and Jones, 1975; Jobse and de Lignie, 1987; Molau, 1993; Gural, 1995; Koten et al., 2003; Koschny et al., 2004). The velocity vector and time of arrival are measured using 60 video cameras spread over three stations in California (+37°N, 122°W). The resulting catalogue of meteoroid orbits is then used to search for groups of meteoroids arriving on orbits similar enough to originate from a common parent body (Southworth and Hawkins, 1963; Galligan, 2003; Jenniskens, 2006; Jopek et al., 2008; Veres and Tóth, 2010; Rozek et al., 2011).

CAMS does so very efficiently, in part because an operator evaluates the quality of each triangulation. In the period from October 2010 to March 2013, during the first 2.5 years of operation, CAMS measured over 100,000 meteoroid orbits in a uniform manner,

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[1] http://www.astro.amu.edu.pl/~jopek/MDC2007/.

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with a median precision slightly better than that of other ongoing video-based multi-station meteoroid orbit surveys (Jenniskens et al., 2011a).

In this paper, we focus on how CAMS detected showers that are already in the IAU List of Established Showers based on other techniques such as photography and radar. CAMS is a significant improvement on the photographic surveys of the past. Many showers established based on photographic data are still in need of accurately determined orbital elements (Jenniskens, 2006, Table 7). Video-based surveillance techniques capture much larger numbers of meteoroid trajectories per hour of observing time, so that streams stand out better from the sporadic background and stream dispersion and components are better defined.

Compared to radar-based surveys such as CMOR (Brown et al., 2008a,b, 2010) that detect fainter meteors (smaller meteoroids) of which there are more, CAMS often detects different showers and is sometimes more sensitive to younger stages of meteoroid stream evolution. Meteor outbursts from crossing cometary dust trails and resonant filaments are frequently detected. CAMS is also comparatively more sensitive to fast (>50 km/s apparent speed) and very slow (<20 km/s) meteors than the radar-based surveys.

CAMS is also well suited to validate results from other ongoing video-based meteoroid orbit survey. The SonotaCo network in Japan has measured meteoroid orbits at a yield of about 25,000 per year since 2007 (Kanamori, 2009). In Europe, the single-station IMO Video Meteor Network is collecting 350,000 (and rising) apparent meteoroid paths in the sky annually (Molau and Barentsen, 2014). As of 2013, 83,369 of these were triangulated and included in the European Video Meteor Network Database EDMOND (Kornos et al., 2012, 2014; Hajduková et al., 2014). Several smaller efforts are ongoing such as, for example, the Croatian Video Network (Vida et al., 2012; Gural et al., 2014). Unlike many of these surveys, CAMS is well documented and has been very uniform both in its data collection and reduction process.

In an earlier paper, we presented the first two months of CAMS observations and the techniques and methods used (Jenniskens et al., 2011a). In this paper, we discuss how the network has evolved since, and present the first 2.5 years of data. Results include median orbital elements for 70 already established nighttime northern hemisphere showers, newly detected shower components, and the detection of meteor outbursts, which provide insight into the dynamical evolution of parent bodies and their meteoroid streams.

2. Methods

Hardware, software, and operational procedures were described in detail in Jenniskens et al. (2011a). The hardware consists of three stations, each containing 20 narrow field-of-view low-light-level *Watec Wat 902H2 Ultimate* video cameras in a weatherproof box. Each station is equipped with a roll-off shutter and contains 19 cameras affixed with a 12-mm *f*/1.2 *Pentax* lens, each with a 30° × 22° field of view, plus one zenith camera with a wider 8-mm *f*/1.4 lens (45° × 33° field of view), together covering the sky above ~30° elevation. Since Nov 27, 2011, these stations are located at Fremont Peak Observatory in Fremont Peak State Park (+36.8°N, 121.5°W), Lick Observatory on Mount Hamilton (+37.3°N, 121.6°W), and at a private residence in Sunnyvale (37.3°N, 122.0°W). The sites are 54–64 km apart. The cameras that contribute to a meteor trajectory are recorded, and the effective survey area is known at all times.

In addition to the three main stations, the CAMS software tools have now been adapted for use on PC, so that amateur astronomers can contribute their own single-CAMS cameras. As of March 2013, three amateur-run single-CAMS stations had come online as part of the California network, each contributing 1–2 cameras, as did a small but growing network of single-CAMS cameras operated in the Netherlands and Belgium (the CAMS@BeNeLux network). They use the same camera and lens configuration to maintain consistent angular resolution. These additional cameras made only a small contribution to the data presented here, but are expected to generate significant yield in the future.

The new single-CAMS software tools include online image processing. Since October 2012, the main stations now also perform image processing on-site, but off-line after each night of observations. The detection algorithms and modules from the MeteorScan software package (Gural, 1995, 1997) are used to detect the meteors and retrieve the astrometric data. The software works on video sequences of 256 frames (NTSC, 29.97 frame-per-second) that are written in a compressed "Four-Frame" format, consisting of 4 video frames that report for each pixel the value for the peak intensity, the frame number in which this occurred, the average temporal intensity, and the associated standard deviation. This saves the temporal propagation history of the meteor and preserves the astrometric accuracy for equatorial coordinate calibration. The 8-s averaged frames typically contain 70–200 stars of +8.1 and brighter, with sub-pixel (~1 arcmin) fitting residuals when employing a cubic polynomial warp in the gnomonic coordinate frame, and ±0.3 magnitude photometric accuracy against the star background. The photometry is corrected for saturation above +1 magnitude, reliable down to about magnitude −5, in a +5.4 stellar limiting magnitude single frame (Jenniskens et al., 2011a).

After reprocessing of the video frames to extract the astrometric position of the meteor, all tracks were gathered in the analysis facility at the SETI Institute, where software for calibration and multi-station coincidence processing combine the data and produce atmospheric trajectories and orbital elements (Jenniskens et al., 2011a). The internet-connected single-CAMS cameras provided the absolute time to about ±1 s, while relative time offsets were calibrated from coincident meteor detections. The Coincidene software is interactive, adding an element of quality control. Each trajectory and light curve solution is projected on-screen, with different colors showing the contribution of each contributing camera. The result is accepted or rejected by an operator based on the lightcurve (brightness versus altitude), a side view of the trajectory (altitude versus downrange), and a top view of the trajectory (latitude versus longitude). Each operator-accepted meteor was only accepted if two selection criteria were met: an apparent radiant better than 2° and apparent speed better than 10%. This removed unacceptably poor tracks and most incorrect solutions that slipped by the operator.

In a modification to earlier reported methods, the data presented here (including previously reported results) were re-calculated with Coincidence version 1.3, in which the trajectory is calculated first by using the intersecting planes method of Ceplecha (1987) and refined using the individual lines of sight to the meteor in sequential video frames. We use the constant frame rate and relative time difference to other cameras in a new approach to combine the data from multiple stations (Gural, 2012).

As a model for the changing observed velocity $V_o(t)$ of the meteoroid moving along the fitted line, we use the empirical equation proposed by Whipple and Jacchia (1957) and Jacchia et al. (1961), which consists of an initial deceleration $a_1a_2^2$ at $t = 0$, which then exponentially increases as defined by the constant a_2. Resulting initial velocities are in good agreement with those expected for meteoroids moving close to the parabolic limit (Jenniskens et al., 2011a). As a correction to Eq. (5a) in Jenniskens et al. (2011a), please note that the term "$+a_1a_2$" in Eq. (5a) is included in the definition of the apparent entry speed V_∞ as tabulated in the meteoroid trajectory and orbit data provided to the Meteor Data Center. The correct equations are (Jacchia et al., 1961):

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