Icarus 275 (2016) 193–202

Contents lists available at ScienceDirect

Icarus

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

Observations of the Quadrantid meteor shower from 2008 to 2012: Orbits and emission spectra

José M. Madiedo[a,b,*], Francisco Espartero[b,c], Josep M. Trigo-Rodríguez[d], Alberto J. Castro-Tirado[e], Pep Pujols[f], Sensi Pastor[g], José A. de los Reyes[g], Diego Rodríguez[h]

[a] Departamento de Física Atómica, Molecular y Nuclear. Facultad de Física., Universidad de Sevilla., 41012 Sevilla, Spain
[b] Facultad de Ciencias Experimentales, Universidad de Huelva, 21071 Huelva, Spain
[c] Observatorio Astronómico de Andalucía, 23688 La Pedriza, Alcalá la Real, Jaén, Spain
[d] Institut de Ciències de l'Espai (CSIC-IEEC), Campus UAB, Facultat de Ciències, Torre C5-parell-2ª, 08193 Bellaterra, Barcelona, Spain
[e] Instituto de Astrofísica de Andalucía, CSIC, Apt. 3004, 18080 Granada, Spain
[f] Grup d'Estudis Astronòmics (GEA) and Agrupació Astronòmica d'Osona, Barcelona, Spain
[g] Observatorio Astronómico de La Murta. Molina de Segura, 30500 Murcia, Spain
[h] Guadarrama Observatory (MPC458), Madrid, Spain

A R T I C L E   I N F O

Article history:
Received 28 September 2015
Revised 21 March 2016
Accepted 16 April 2016
Available online 26 April 2016

Keywords:
Meteorites
Meteors
Near-Earth Objects

A B S T R A C T

The activity of the Quadrantids in January during several years (2008, 2010, 2011 and 2012) has been investigated in the framework of the SPanish Meteor Network (SPMN). For this purpose, an array of high-sensitivity CCD video devices and CCD all-sky cameras have been used to obtain multi-station observations of these meteors. These allowed to obtain precise radiant and orbital information about this meteoroid stream. This paper presents a large set of orbital data (namely, 85 orbits) of Quadrantid meteoroids. Most meteors produced by these particles were recorded during the activity peak of this shower. *Besides, we discuss four Quadrantid emission spectra. The tensile strength of Quadrantid meteoroids has been also obtained.*

1. Introduction

The Quadrantid meteor shower was first identified in 1835 (Fischer, 1930; Lovell, 1954), and no records of this shower earlier than the beginning of the 19th century appear to exist (Williams and Colander-Brown, 1998). Its activity extends from about December 31 to January 6, peaking around January 4 (Jenniskens, 2006). Besides, this peak is very short, being less than a day (Shelton, 1965; Williams et al., 1979).

For many years the parent of the Quadrantid stream was unknown though many suggestions were made (see Williams and Collander-Brown, 1998 for a list). The two most likely candidates were Comet 96P/Machholz (McIntosh, 1990) and Comet 1490I (Hasegawa, 1979; Williams and Wu, 1993). Jenniskens (2004) showed that asteroid 2003EH1 and the Quadrantids had an exceedingly similar orbit and that there must be a generic relationship between them. In that paper Jenniskens suggested that the fragmentation of Comet 1490I at some later date might have led to the formation of both 2003EH1 and the core of the Quadrantids. This suggestion was investigated further by Williams et al. (2004). Neslušan et al. (2013) have argued that the Quadrantids and 2003EH1 resulted from a break-up of Comet 96P/Machholz, thus explaining both the core and the broad component of the Quadrantids. Jopek and Williams (1993) took the interrelationship idea further, suggesting that a proto-Machholz fragmented to form both the present day Machholz and 1490I, with a further fragmentation producing 2003 EH1 and the Quadrantids.

The observations of the Quadrantids are not abundant. Thus, despite having the highest zenithal hourly rate (ZHR) of all annual meteor showers (about 130 meteors per hour), its short activity period and frequent unfavourable weather conditions in early January pose important difficulties to the observation of this shower. This short activity period makes the total amount of observing time very short each year. Hence the advantage of accumulating several years of observations. Wu and Williams (1992) published the first large set of precisely reduced orbits of Quadrantid meteoroids, which consisted of 118 orbits. Jenniskens et al. (1997) produced a list of 64 Quadrantid orbits. A continuous monitoring of meteor and fireball activity from sites offering good probabilities of optimal weather conditions is very convenient in order to anal-

* Corresponding author at: Facultad de Ciencias Experimentales, Universidad de Huelva, 21071 Huelva, Spain. Tel.: +34 959219991.
E-mail address: madiedo@cica.es, jmmadiedo@gmail.com (J.M. Madiedo).

http://dx.doi.org/10.1016/j.icarus.2016.04.023
0019-1035/

Table 1
Geographical coordinates of the SPMN meteor observing stations involved in this work.

Station #	Station name	Longitude	Latitude (N)	Alt. (m)
1	Sevilla	5° 58′ 50″ W	37° 20′ 46″	28
2	Cerro Negro	6° 19′ 35″ W	37° 40′ 19″	470
3	La Hita	3° 11′ 00″ W	39° 34′ 06″	674
4	Huelva	6° 56′ 11″ W	37° 15′ 10″	25
5	La Murta	1° 12′ 10″ W	37° 50′ 25″	400
6	Sierra Nevada	3° 23′ 05″ W	37° 03′ 51″	2896
7	El Arenosillo	6° 43′ 58″ W	37° 06′ 16″	40
8	Folgueroles	2° 19′ 33″ E	41° 56′ 31″	580
9	OAdM (Montsec)	0° 43′ 46″ E	42° 03′ 05″	1570
10	Montseny	2° 31′ 14″ E	41° 43′ 17″	300

yse this stream. One of these locations within continental Europe is the Iberian Peninsula, particularly the South of Spain. This has provided the opportunity to observe the Quadrantids in recent years from several meteor stations operating in the framework of the SPMN. Here we provide 85 orbits obtained for multi-station Quadrantid meteors imaged between 2008 and 2012. Four emission spectra produced during the ablation of particles belonging to this meteoroid stream are also presented and discussed.

2. Instrumentation and methods

Several meteor observing stations located in Spain were involved in the monitoring of the activity of the Quadrantid meteor shower from 2008 to 2012. Their locations are listed in Table 1. Except for station #9, which operates an all-sky slow-scan CCD camera, these stations employ an array of low-light CCD video cameras (models 902H and 902H Ultimate, from Watec Co.) to obtain meteor atmospheric trajectories and meteoroid orbits (Madiedo and Trigo-Rodríguez, 2008; Trigo-Rodríguez et al., 2007). The video cameras are equipped with a 1/2″ Sony interline transfer CCD image sensor with their minimum lux rating ranging from 0.01 to 0.0001 lx at f1.4. Aspherical lenses are employed. Their focal length ranges from 6 to 25 mm and the field of view covered by each device ranges from 62×50 to 14×11 degrees. In this way, different areas of the sky can be monitored by every camera and point-like star images are obtained across the entire field of view. These cameras generate interlaced imagery according to the PAL video standard, at a rate of 25 frames per second and with a resolution of 720×576 pixels. Most of our video stations develop a continuous monitoring of the night sky and work in an autonomous way by means of the MetControl software (Madiedo et al., 2010; Madiedo 2014). However, station #2 (Cerro Negro) is a mobile system which is set-up when necessary in a dark countryside environment at about 60 km north from Seville. A detailed description of the all-sky CCD system operating at station #9 can be found in Trigo-Rodríguez et al. (2007). Aspherical fast lenses with focal lengths ranging from 4 to 12 mm and focal ratios between 1.2 and 0.8 were used. In this way, different areas of the sky were covered by every camera and point-like star images were obtained across the entire field of view. With this configuration we can image meteors with an apparent magnitude of about 3 ± 1. The images taken by the cameras are sent to an array of PC computers which are automatically synchronized by means of GPS devices. In this way, meteor recording times are known with an accuracy of 0.1 seconds. A more detailed description of the operation of these systems can be found in (Madiedo and Trigo-Rodríguez, 2008; Madiedo et al., 2010). To reduce the images containing meteor trails we have followed the procedure described in (Madiedo et al., 2013a). Thus, at the end of every observing session data recorded during the night were automatically compressed and sent to our FTP server. This is not the case for the mobile station at Cerro Negro, where the video files were manually saved to the server's hard disk. Once the images recorded by every station were stored on the FTP server, another software package identified trails that were simultaneously recorded from at least two different stations. A copy of these multi-station data was placed in a separate folder where the video frames on each video file were co-added in order to increase the number of stars available for the astrometric measurement. A composite image showing the whole meteor trail was also generated for each event. Then, an astrometric measurement was done by hand in order to obtain the plate (x, y) coordinates of the meteor along its apparent atmospheric path from each station. These astrometric measurements were introduced in the AMALTHEA software (Trigo-Rodríguez et al., 2009a,2009b; Madiedo et al., 2011), which was developed by the first author and employs the methods described in (Ceplecha, 1987) to obtain the atmospheric trajectory of the meteor and the orbital elements of the progenitor meteoroid.

In order to count meteors occurring during our survey in 2011, a forward-scatter radio system operating at a frequency of 143.05 MHz was operated. This was located in Collado Villalba (Madrid), and employed a 2.15 dBi discone antenna (model Diamond D-130) connected to a Yaesu VR 5000 radio receiver. This device received the reflections from the Grand Réseau Adapté à la Veille Spatialle (GRAVES) radar, located in Dijon, France (http://www.onera.fr/dcps/graves).

Another aim of this research was to obtain emission spectra of Quadrantid meteors. To accomplish this task, holographic diffraction gratings were attached to the lens of some of our CCD video cameras. These gratings had 500 or 1000 grooves per mm, depending on the device. The emission spectra recorded in the framework of this survey have been analysed with the CHIMET software, which is able to identify and measure emission lines in these signals (Madiedo et al., 2013b).

3. Results

Variable weather conditions were found each year. Thus, bad weather over Spain made data acquisition impossible for SPMN stations during January 1–3, 2008. That year our first data were collected during January 3–4 from two stations located in Andalusia: Sevilla and the mobile system at Cerro Negro. The mobile system was setup during the afternoon of January 3 in order to provide a double-station system coordinated with our station at Seville during the period of maximum activity of the Quadrantid shower, which according to the information provided by the International Meteor Organization (IMO) was predicted to peak on January 4 at 6 h 40 m UTC (www.imo.net). Nevertheless, weather conditions were completely unfavourable during the first hours after sunset, since the sky was completely cloudy in Cerro Negro and scattered showers were present also in the Seville area. Despite this, the devices at the mobile station remained ready for operation and covered with sheets of plastic to protect them from the rain, in order to make profit of an eventual improvement in weather conditions. Fortunately this improvement took place around 2 h 10 m UTC and the Quadrantids could be observed during the predicted peak, together with a number of transient luminous events (TLE) in the atmosphere (sprites) that were also recorded.

In January 2009, bad weather conditions did not allow obtaining any double station Quadrantid meteors, despite our meteor network was expanded and four additional observing stations were available by that time. Thus, just single station Quadrantid trails were imaged, and so no orbital data could be inferred from these. In January 2010, unfavourable weather interfered with the observation of this shower again, and just stations #8, 9 and 10, located in the north of Spain, could image some double-station