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Ozone measurements with meteors: a revisit

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ABSTRACT

Understanding the role of ozone in the mesosphere/lower thermosphere (MLT) region is essential for understanding the atmospheric processes in the upper atmosphere. Earlier studies have shown that it is possible to use overdense meteor trails to measure ozone concentration in the meteor region. Here, we revisit this topic by comparing a compilation of radar observations to satellite measurements. We observe a modest agreement between the values derived from these two methods, which confirm the usefulness of the meteor trail technique for measuring ozone content at certain heights in the MLT region. Future simultaneous measurements will help quantifying the performance of this technique.

Key words: Earth – meteorites, meteors, meteoroids.

1 INTRODUCTION

A *meteor* is the visible streak of light produced by an interplanetary dust particle (a *meteoroid*) at the entry of the Earth's atmosphere. Meteoroids are directly linked to the primitive materials in the early Solar system: they are either leftovers of the planet formation era in the early Solar system, or are linked to primitive bodies (asteroids and comets), and therefore they attract intense interests in the astrophysics and planetary science communities.

The atmospheric science community, on the other hand, has used the meteor phenomenon as a tool to study the atmospheric properties and dynamics of the so-called meteor region within the mesosphere/lower thermosphere (MLT) since the 1950s. This is a region 70–120 km above Earth's surface is generally difficult to study with *in situ* techniques. Radar meteor techniques, in particular, have been used to infer atmospheric properties such as high-altitude temperature and winds (e.g. Fraser 1965; Cervera & Reid 1995; Hocking 1999; Younger et al. 2008, 2014, and many others), planetary-scale features (Cevolani 1991; Baggaley et al. 2001), and ozone concentration (e.g. Jones, McIntosh & Simek 1990; Jones & Simek 1995; Hajduk et al. 1999; Cevolani & Pupillo 2003). Determination of the ozone concentration uses the fact that the duration of overdense meteor trails are concurrently limited by ambipolar diffusion at high altitudes and oxidation due to the presence of ozone at lower heights as first recognized by Baggaley (1972).

Ozone plays a major role at high altitudes (50–100 km) in the chemistry of the upper atmosphere (c.f. Allen, Lunine & Yung 1984, and references therein), yet measurements of ozone in the MLT remain relatively scarce. Stellar occultation technique has been routinely used to measure mesospheric ozone content since 1970s (e.g. Hays & Roble 1973; Bevilacqua et al. 1996; Kaufmann et al. 2003; Kyrölä et al. 2006), but only a handful of these surveys extend their measurements to MLT and even if they do, the uncertainty in the MLT region is considerably higher. The 1.27 μm^{-1} airglow emission is another technique that has been used to derive MLT ozone content (e.g. Sica & Lowe 1993; Gumbel et al. 1998), but it depends on the assumption of a steady-state photochemical model that does not always holds in the MLT region (Zhu, Yee & Talaat 2007). An alternative technique will be helpful in providing an independent measurement of the ozone content in the MLT region.

Jones et al. (1990) were the first to suggest a method whereby the distribution of overdense meteor echo durations could be used to estimate ozone levels at a particular height. In the absence of chemistry-limiting reactions, the cumulative distribution of echo duration should be a power-law reflecting the distribution in the masses of incoming meteoroids, as the duration of an overdense echo subject to ambipolar diffusion is directly related to the mass of the original meteoroid (e.g. Ceplecha et al. 1998). Chemical reactions remove electrons from the trail and this process exceeds diffusion at longer durations. Therefore, the resulting cumulative distribution shows a break or inflection in the original power law. The location of this inflection is a direct estimate of the ozone concentration at the height appropriate to the knee in the distribution.

Several dedicated, long-term meteor radar systems, such as the Advanced Meteor Orbit Radar in 1990–1999 (Baggaley 1995), the Canadian Meteor Orbit Radar (CMOR) from 2002 onwards (Jones et al. 2005) and meteor radars at Antarctica from 2006 onwards (Holdsworth et al. 2008; Younger et al. 2009), each have collected orders of magnitude more data than their precursors. However,

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unlike temperature and wind measurements, which rely on underdense meteor trails that are relatively easy to identify with automatic algorithms, determination of ozone concentration relies on the precise measurement of the duration of overdense meteor trails, a process that is difficult to automate. Therefore, ozone study takes little advantage from the dramatic increase of meteor data.

Here, we revisit this topic combining results of a number of earlier studies, including several CMOR data sets that are recently analysed and published (Ye et al. 2013a,b, and others). Our goal is to compare the resulting ozone estimates with more recent satellite estimates of ozone with overlapping temporal coverage, updated reaction rate coefficients and critically review the utility of this technique for providing ozone concentrations at specific heights.

2 THEORY: A REVISIT

The mass distribution index is defined such that the number of meteoroids in the mass interval $(m, m + dm)$ follows m^{-s} (McKinley 1961; Grun et al. 1985). In most cases, the assumption of a power-law distribution of meteoroid number as a function of mass holds for a wide mass range, although in practice, most streams are found to have a unique s.

It is difficult to directly measure the mass of an individual meteoroid, but following classic radar meteor theory, we expect the mass of a meteoroid to be linearly proportional to the (peak) electron line density q of the trail formed (for underdense meteor trails) or the *height-corrected* (Simek 1987) duration τ (for overdense meteor trails) as seen by the radar. Therefore, the distribution of q or τ can be used to constrain s. This can be done by simply counting the cumulative number of meteors N beyond a certain value of q or τ and measure the slope of the linear portion to derive s (McIntosh 1968):

$$N \propto q^{1-s} \tag{1}$$

for underdense trails, or

$$N \propto \tau^{3(1-s)/4} \tag{2}$$

for overdense trails.

Equation (2) provides the theoretical duration of an overdense meteor trail when the decay process is dominated by ambipolar diffusion. Larger/slower meteoroids can survive to lower heights (below ∼100 km), where the duration can be limited by the reaction rate of a two-body attachment process between meteoric electrons, called the *chemistry-limited regime*. Diffusion of meteor trails above ∼100 km are predominately controlled by ambipolar process and is not considered susceptible to chemistry-limited regime.

The duration in the chemistry-limited regime is expressed as follow (Jones et al. 1990, section 1), although it has been recognized that the change of power beam collecting area can alter its slope (Pecina 1984; Pecinová & Pecina 2005):

$$N \propto \tau^{9(1-s)/2}. \tag{3}$$

However, the derived s values showed large discrepancies with values derived from independent techniques (e.g. optical measurements), possibly due to the non-negligible contributions from other factors, such as gravity waves or charged dust particles (e.g. Kelley 2004). Nonetheless, the transition between diffusion-limited regime and chemistry-limited regime is marked by the 'characteristic' duration, t_c (Fig. 1). Trails with duration greater than t_c are predominantly in the chemistry-limited regime and vice versa.

Baggaley & Cummack (1974) attribute the cause of chemistry-limited regime to rapid dissociative recombination between meteoric ions and ozone molecules, which was later supported by observational evidence (Jones et al. 1990). The key reactions removing electrons from the trail are:

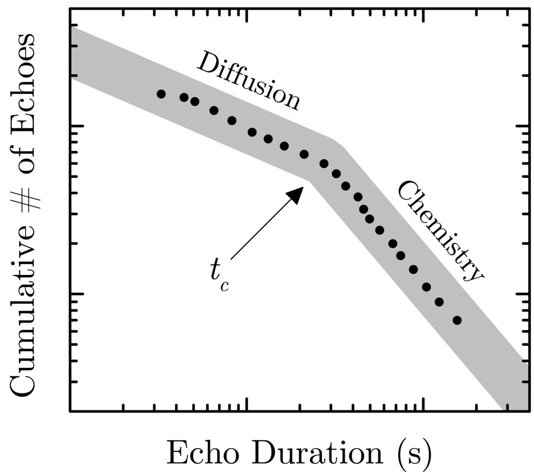

Figure 1. The determination of the characteristic duration, t_c, presented as a turnover point from diffusion-limited regime to chemistry-limited region. This illustrative figure does not involve real data.

$$M^+ + O_3 \rightarrow MO^+ + O_2, \tag{4}$$

$$MO^+ + e \rightarrow M + O, \tag{5}$$

where M^+ is the meteoric ion. The reaction constant of Reaction 4 is two to three orders of magnitude slower than Reaction 5 (Whalley et al. 2011; Plane & Whalley 2012), which limits the de-ionization process. We should note that this reaction is only dominant above ∼88 km (Ferguson & Fehsenfeld 1968; Rowe et al. 1981; Whalley et al. 2011), hence limiting the heights that the meteor trail technique can be applied.

Readers may also wonder about the reaction

$$MO^+ + O \rightarrow M^+ + O_2 \tag{6}$$

which dominates over Reaction 5 in the background MLT. However, it should be noted that in *overdense* meteor trails, the electron density (∼10^{20} m^{-3}; e.g. Foschini 1999) is much higher than the ambient atomic oxygen density (∼10^{18} m^{-3}; e.g. Lednyts'kyy et al. 2015), and therefore, Reaction 5 will dominate over Reaction 6 in the overdense meteor trails.

Taking the reaction constant of Reaction 4 to be k, the ozone concentration can be calculated by

$$[O_3] = \frac{1}{kt_c} \tag{7}$$

as applicable to the knee height of the meteors, namely the 'knee' height where t_c applies.

For simplicity, Mg^+ has been used as the representative species for major meteoric ions (e.g. Cervera & Reid 2000; Younger et al. 2014). However, it is known that other species that participate the oxidation process, such as Si^+ and Fe^+, are also major ion species in meteoroids (Baggaley & Cummack 1974). Although oxidation with Mg^+ ion is slightly more efficient than that of Si^+ and Fe^+ (Table 1), some meteoroid streams (such as η-Aquariids and Orionids) are known to be Si-rich (Jessberger, Christoforidis &

Table 1. Weight and combined rate constant (k) derived for each meteoroid stream. For abundance ratio, numbers in brackets indicate that ratio for the respective stream is unknown; therefore, generalize value from carbonaceous (CI) chondrite (Anders & Grevesse 1989) is used. Rate constants for oxidation of individual species are $(1.17 \pm 0.19) \times 10^{-15}$ m^3 mol^{-1} s^{-1} for $Mg^+ + O_3$ (Whalley et al. 2011), $(6.5 \pm 2.1) \times 10^{-16}$ m^3 mol^{-1} s^{-1} for $Si^+ + O_3$ (Gomez Martin & Plane 2011) and $(7.1 \pm 2.3) \times 10^{-16}$ m^3 mol^{-1} s^{-1} for $Fe^+ + O_3$ (Rollason & Plane 1998).

Shower	Element	Abundance (fraction)	Weight (w_i)	k (m^3 mol^{-1} s^{-1})	Reference
Camelopardalids	Mg	(0.36)	0.16	7.76×10^{-16}	Anders & Grevesse (1989)
	Si	(0.34)	0.15		
	Fe	(0.30)	0.68		
Perseids	Mg	0.37	0.29	8.09×10^{-16}	Borovička (2005)
	Si	0.52	0.55		
	Fe	0.11	0.16		
Draconids	Mg	0.42	0.18	7.79×10^{-16}	Borovička, Spurný & Koten (2007)
	Si	(0.31)	0.27		
	Fe	0.27	0.55		
Geminids	Mg	0.52	0.31	8.36×10^{-16}	Kasuga, Watanabe & Ebizuka (2005)
	Si	(0.25)	0.27		
	Fe	0.23	0.42		

Kissel 1988). If we take the whole process as a simple stoichiometric reaction, we have

$$k = \sum_{i=1}^{N} w_i k_i, \tag{8}$$

where w_i and k_i denote the weight and reaction constant, respectively, of the ith chemical species, which is either Mg^+, Si^+ or Fe^+ in our work. The weight is derived using relative abundance and fraction of ionization reported in earlier papers (Jones 1997; Vondrak et al. 2008) for each meteoroid stream. We follow Baggaley & Cummack (1974)'s suggestion that Mg^+, Si^+ and Fe^+ make up 93 per cent of meteoric ions and assume Mg^+, Si^+ and Fe^+ are fully responsible for oxidation process (the remaining 7 per cent is attributed to Na^+ which does not take part in the oxidation process).

3 DATA COLLECTION AND RESULTS

We compiled a total of nine reported height-corrected characteristic times t_c, including data from nine meteoroid streams recorded by five radar systems with observations dating back to 1957. Unfortunately, most of the works do not report the uncertainty of their data. Moreover, the process of fitting is not always clearly documented, making the results difficult to reproduce. Hence, we re-measure and re-fit all data set using a linear piecewise function which will also give us the fitting error. All re-measured t_c agree the original values within ∼30 per cent. We then converted t_c to ozone concentration using equations (7) and (8) with weights and combined reaction constants for the corresponding meteoroid stream. The results are shown in Table 2 and Fig. 2.

With regard to the determination of the knee height, or the knee height of the meteors, there are three approaches:

(i) Interferometric observations: The specular height of every observed meteor is measured directly by the radar. The knee height can therefore be taken as the mean inflection height of the meteors in the sample.

(ii) Simultaneous radar-visual observations (Jones et al. 1990): Meteors are simultaneously observed by radar and a set of visual observers, the knee height is derived using the relation between meteor luminosity and its radio duration (McKinley 1961, sections 8–13).

(iii) Photographic observations: It applies to the radar systems with no interferometer or simultaneous visual observations. The average meteor luminosity is taken from other photographic or video meteor surveys (e.g. Jacchia, Verniani & Briggs 1967; Brown et al. 2002), allowing knee height to be derived using luminosity–duration relation. Jones & Simek (1995) show that the uncertainty of this method is ∼3 km.

CMOR is equipped with an interferometer; Springhill is accompanied by visual observers. The other two radar systems (Ondřejov and Kharkov) use photographic mean determined by Jacchia et al. (1967) and Brown et al. (2002, for Leonids) to derive the knee height.

We then compared our results to those derived from SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) instrument on the TIMED (Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics) satellite that measures ozone profile using star occultation by Earth's atmosphere. The 9.6 µ m^{-1} ozone data obtained by SABER in March, June, September and December in 2002–2013 within 10° longitude and 5° latitude around CMOR site are extracted from the level 2 V2.0 data sets as available through the SABER website (http://saber.gats-inc.com/index.php).

As shown in Fig. 2, we observe a modest agreement between the meteor-derived values and SABER measurements within the region which the meteor trail method is valid (88–100 km): all meteor-derived data points are within the range of diurnal variation of ozone as measured by SABER. This confirms earlier studies that meteor trail technique is effective. Beyond the 88–100 km region, the meteor-derived value still show some trend of agreement with the SABER values, but it is difficult to judge how far this agreement extend beyond the valid region and whether it can be trusted.

However, the lack of time information of the meteor data prevent us to compare the meteor data and SABER data more directly (i.e. data taken at the same time). This prompts us to focus on data from meteor outbursts only. There are three meteor outburst events in our data set: the Draconid outbursts in 2011 October 8 (16–20 h UT) and 2012 October 8 (15–19 h UT) (Ye et al. 2013a,b), and the Camelopardalid outburst in 2014 May 24 (4–12 h UT) (Ye & Wiegert 2013). Meteor outburst is a phenomenon in which meteor

Table 2. Summary of characteristic time measurements and the derived ozone concentrations (in part per million volumes).

Shower	Radar	Year of observation	t_c (s)	Knee (km)	[O_3] (ppmv)	Reference
Camelopardalids	CMOR	2014	1.6 ± 0.1	85	3.72 ± 0.22	Ye et al. (2016)
Perseids	Ondřejov	1991	21.1 ± 2.5	96	2.43 ± 0.26	Jones & Simek (1995)
	Springhill	1957–1982	34.6 ± 4.5	97	1.78 ± 0.20	Jones & Simek (1995)
Draconids	CMOR	2011	2.7 ± 0.2	87	3.93 ± 0.27	Ye et al. (2013b)
	CMOR	2012	2.5 ± 0.2	89	6.07 ± 0.45	Ye et al. (2013a)
	Springhill	1985	13.1 ± 0.9	94	2.83 ± 0.18	Simek (1994)
Geminids	Ondřejov	1958–1991	5.0 ± 0.4	83	1.01 ± 0.07	Jones & Simek (1995)
	Kharkov	1958	4.6 ± 0.3	83	1.10 ± 0.07	Jones & Simek (1995)
	Springhill	1957–1982	13.8 ± 0.6	86	0.60 ± 0.02	Jones & Simek (1995)

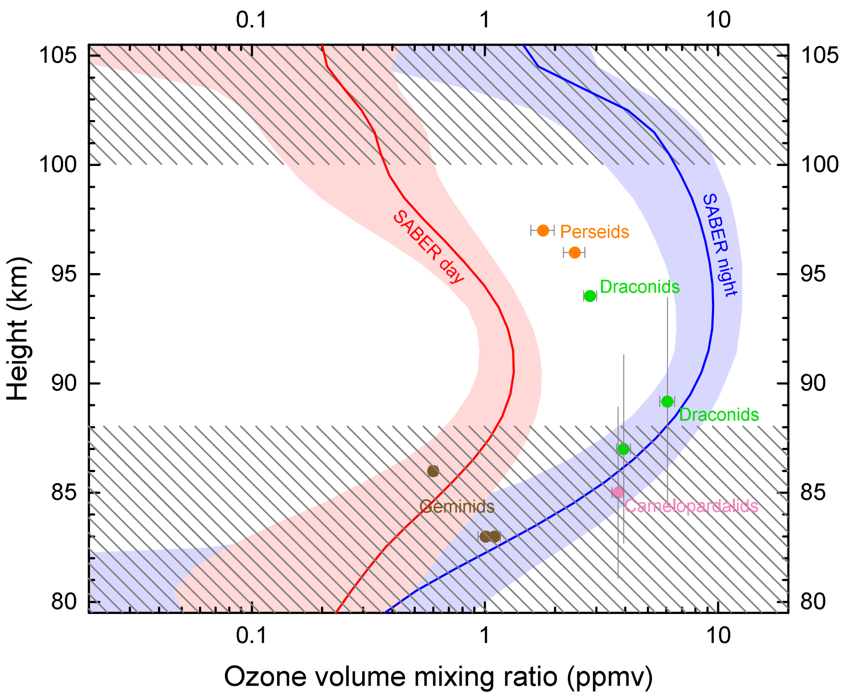

Figure 2. Ozone mixing ratio (in part per million volumes) derived from meteor trails and SABER. Uncertainty bars indicate the standard deviation of the SABER and meteor-derived data. Shaded area indicates region that the meteor technique is theoretically invalid.

rate from a particular meteoroid stream increases significantly, usually just in a few hours. The increase of meteor rate helps to improve the statistics, while the short duration helps by reducing the potential blur caused by temporal variation of ozone content. However, this introduces another difficulty as SABER do not always have observations in the desired time period. To increase the statistics at the SABER end, we include SABER data taken in the same hours within 5 d from the outburst dates. Still, the SABER data taken at both Draconid dates were 4–6 h too early for the outbursts, which would translate to an ozone level about two times lower compared to the ozone level at the outburst times which were both at local noon (Huang et al. 2008, fig. 8b).

As shown in Fig. 3, the results are unfortunately suffered from low statistics, as well as suffered from the fact that most data points are beyond the valid zone for the meteor trail technique. Future campaigns aiming at collecting more simultaneous measurements will be useful to evaluate the performance of the meteor trail technique.

We also note that the compositional difference among the streams seems to have minor impact on the derivation of ozone. Our sample covers a wide range of compositions, from Mg-rich (such as Draconids) to Si-rich (such as Perseids), but the resulting combined rate constants are within ~5 per cent from each other. These showers are major annual showers that can be considered to be representative to shower meteors. Despite Mg^+ having a higher rate constant, the ionization fraction of Mg is always lower than that of Si and Fe within the entire speed range, thus the Mg^+ reaction will not dominate under any circumstance.

4 SUMMARY

We revisited the technique of using overdense meteor trails to measure ozone content in the MLT region. The technique was examined by comparing data derived from radar meteor observations to the ones derived from satellite observations. We observe a modest agreement between the two, confirming the results reported by earlier studies. However, the lack of simultaneous measurements made by different techniques prevent further evaluation about the performance of the meteor technique. Future campaigns focused

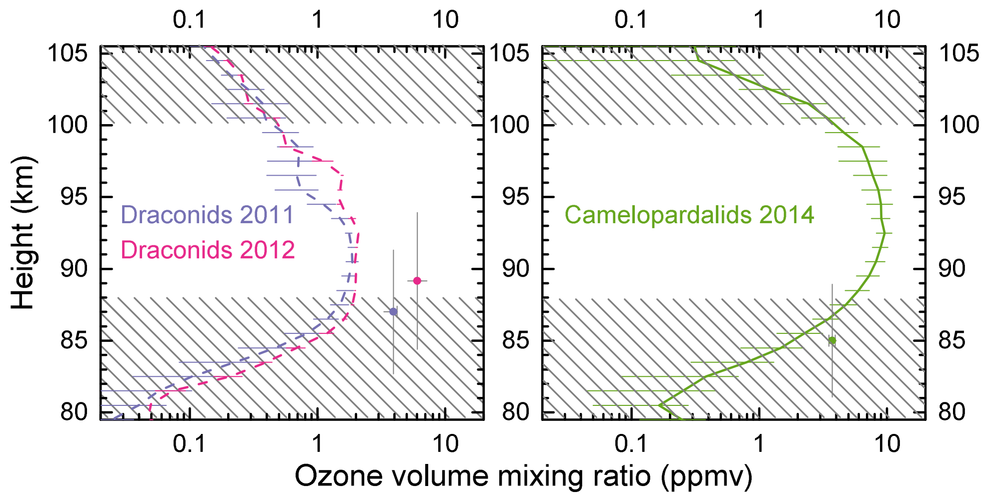

Figure 3. Semisimultaneous ozone measurements by CMOR (circles) and SABER during Draconids outbursts in 2011 and 2012 (left) and Camelopardalids outburst in 2014 (right). CMOR measurements are appropriated to 2011 October 8 at 16–20 h UT and 2012 October 8 at 15–19 h UT for the Draconids, and 2014 May 24 at 4–12 h UT for the Camelopardalids. SABER observations are conducted at similar hours within five days from the outburst dates. SABER profiles appropriated for the Draconid outbursts are plotted in dashed lines, as the observations are 4–6 h too early for the meteor-derived value. Uncertainty bars for SABER profile and CMOR data indicate the standard deviation of the data. Shaded area indicates region that the meteor technique is theoretically invalid.

in collecting more simultaneous measurements of the meteor technique and other techniques would be useful to resolve this issue.

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REFERENCES

Allen M., Lunine J. I., Yung Y. L., 1984, J. Geophys. Res. Atmos., 89, 4841
Anders E., Grevesse N., 1989, Geochim. Cosmochim. Acta, 53, 197
Baggaley W. J., 1972, MNRAS, 159, 203
Baggaley W., 1995, Earth Moon Planets, 68, 127
Baggaley W. J., Cummack C. H., 1974, J. Atmos. Terr. Phys., 36, 1759
Baggaley W. J., Marsh S. H., Bennett R. G. T., Galligan D. P., 2001, in Warmbein B., ed., ESA SP-495: Meteoroids 2001 Conference. ESA, Noordwijk, p. 387
Bevilacqua R. M. et al., 1996, Geophys. Res. Lett., 23, 2317
Borovička J., 2005, Modern Meteor Science an Interdisciplinary View. Springer, Dordrecht, the Netherlands, p. 245
Borovička J., Spurný P., Koten P., 2007, A&A, 473, 661
Brown P., Campbell M. D., Hawkes R. L., Theijsmeijer C., Jones J., 2002, Planet. Space Sci., 50, 45
Ceplecha Z., Borovička J., Elford W. G., Revelle D. O., Hawkes R. L., Porubčan V., Šimek M., 1998, 327
Cervera M. A., Reid I. M., 1995, Radio Sci., 30, 1245
Cervera M. A., Reid I. M., 2000, Radio Sci., 35, 833
Cevolani G., 1991, Geophys. Res. Lett., 18, 1987
Cevolani G., Pupillo G., 2003, Ann. Geophys., 46
Ferguson E., Fehsenfeld F., 1968, J. Geophys. Res., 73, 6215
Foschini L., 1999, A&A, 341, 634
Fraser G., 1965, J. Atmos. Sci., 22, 217
Gomez Martin J. C., Plane J. M. C., 2011, Phys. Chem. Chem. Phys., 13, 3764
Grun E., Zook H. A., Fechtig H., Giese R. H., 1985, Icarus, 62, 244
Gumbel J., Murtagh D. P., Espy P. J., Witt G., Schmidlin F. J., 1998, J. Geophys. Res. Space Phys., 103, 23399
Hajduk A., Hajduková M., Porubčan V., Cevolani G., Grassi G., 1999, in Baggaley W. J., Porubcan V., eds, Proceedings of the International Conference held at Tatranska Lomnica, Slovakia, 1998 August 17–21, p. 91
Hays P. B., Roble R. G., 1973, Planet. Space Sci. 21, 273
Hocking W., 1999, Geophys. Res. Lett., 26, 3297
Holdsworth D. A., Murphy D. J., Reid I. M., Morris R. J., 2008, Adv. Space Res., 42, 143
Huang F. T., Mayr H. G., Russell J. M., Mlynczak M. G., Reber C. A., 2008, J. Geophys. Res. Space Phys., 113, 4307
Jacchia L., Verniani F., Briggs R. E., 1967, Smithson. Contrib. Astrophys., 10, 1
Jessberger E. K., Christoforidis A., Kissel J., 1988, Nature, 332, 691
Jones W., 1997, MNRAS 288, 995
Jones J., Simek M., 1995, Earth Moon Planets, 68, 329
Jones J., McIntosh B. A., Simek M., 1990, J. Atmos. Terr. Phys., 52, 253
Jones J., Brown P., Ellis K., Webster A., Campbell-Brown M., Krzemenski Z., Weryk R., 2005, Planet. Space Sci., 53, 413
Kasuga T., Watanabe J., Ebizuka N., 2005, A&A, 438, L17
Kaufmann M., Gusev O. A., Grossmann K. U., MartÃn-Torres F. J., Marsh D. R., Kutepov A. A., 2003, J. Geophys. Res. Atmos., 108
Kelley M. C., 2004, Radio Sci., 39, RS2015
Kyrölä E. et al., 2006, J. Geophys. Res., 111, D24306
Lednyts'kyy O., von Savigny C., Eichmann K.-U., Mlynczak M. G., 2015, Atmos. Meas. Tech., 8, 1021
McIntosh B. A., 1968, in Kresak L., Millman P. M., eds, Proc. IAU Symp. 33, Physics and Dynamics of Meteors. Springer-Verlag, New York, p. 343
McKinley D. W. R., 1961, Meteor Science and Engineering. New York, McGraw-Hill
Pecina P., 1984, Bull. Astron. Inst. Czech., 35, 183
Pecinová D., Pecina P., 2005, Modern Meteor Science an Interdisciplinary View. Springer Netherlands, Amsterdam, p. 689
Plane J. M., Whalley C. L., 2012, J. Phys. Chem. A, 116, 6240
Rollason R. J., Plane J. M. C., 1998, J. Chem. Soc., Faraday Trans., 94, 3067
Rowe B., Fahey D., Ferguson E., Fehsenfeld F., 1981, J. Chem. Phys., 75, 3325
Sica R., Lowe R., 1993, J. Geophys. Res., 98, 1051
Simek M., 1987, Bull. Astron. Inst. Czech., 38, 80

Simek M., 1994, A&A, 284, 276
Vondrak T., Plane J. M. C., Broadley S., Janches D., 2008, Atmos. Chem. Phys. Discuss., 8, 14557
Whalley C. L., Martin J. C. G., Wright T. G., Plane J. M. C., 2011, Phys. Chem. Chem. Phys., 13, 6352
Ye Q., Wiegert P. A., 2013, MNRAS, 437, 3283
Ye Q., Wiegert P. A., Brown P. G., Campbell-Brown M. D., Weryk R. J., 2013a, MNRAS, 436, 675
Ye Q., Brown P. G., Campbell-Brown M. D., Weryk R. J., 2013b, MNRAS, 436, 675
Ye Q.-Z., Hui M.-T., Brown P. G., Campbell-Brown M. D., Pokorný P., Wiegert P. A., Gao X., 2016, Icarus, 264, 48
Younger J. P., Reid I. M., Vincent R. A., Holdsworth D. A., 2008, Geophys. Res. Lett., 35
Younger J. P., Reid I. M., Vincent R. A., Holdsworth D. A., Murphy D. J., 2009, MNRAS, 398, 350
Younger J., Lee C., Reid I., Vincent R., Kim Y., Murphy D., 2014, J. Geophys. Res. Atmos., 119, 10027
Zhu X., Yee J.-H., Talaat E. R., 2007, J. Geophys. Res. Atmos., 112

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