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Meteoroid Flaring as a Possible Source of Intense Langmuir Waves

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Abstract

We introduce observational evidence obtained using the co-axial 430 MHz and 46.8 MHz radars at Arecibo Observatory for meteoroid flare processes that produce radar detectable scattering 1-2 kilometers delayed from the point of the flare on the meteoroid trajectory through the atmosphere. While several such events have been observed, we concentrate on one particularly interesting event. For this ~90 km event, the head-echo at both frequencies is indicative of multiple fragments and of flaring based on the approach described by Mathews et al. [1]. The UHF radar meteor head-echo yields evidence of two major fragments but did not show the meteoroid flare while only the much less sensitive but wider-beam VHF radar revealed the unusual "delayed-echo" feature as well as complex fragmentation and the progenitor flare. For this event the flare and the resultant *delayed-echo* feature were well defined in the Range-Time-Intensity results and together point to an apparent propagation speed of the process giving rise to the *delayed-echo* of 50-100 km/sec. This is far too fast for shock waves thus pointing to intense plasma waves generated in the presumably "explosive" termination of a meteoroid fragment that produced the intense, well-defined radar flare-echo. We assume that the plasma "waves" generated by the explosive flare propagate in the trail-plasma "waveguide" and produce strong, highly non-thermal perturbations in the distribution of the trail-plasma thus engendering the observed strong VHF radar scattering at 1-2 km delay from the flare. We note convincing recent reports [2 and references therein] of transient HF/VHF radio emissions seen from the LWA1 (Long Wavelength Array prototype) and identified as originating from along the trajectory of optical bolides observed by a network of meteor cameras. Obenberger et al. [2] attribute these emissions to mode conversion to RF of Langmuir waves in the large gradients of the trail plasma. We agree with this assessment and, based on our *delayed-echo* results, further suggest that the meteoroid flaring generates these waves and also that the waves are contained within the trail-plasma waveguide thus limiting dissipation. We have not seen evidence of RF emission in our observations.

1. Introduction

We herein update our earlier reports [3,4] on Arecibo Observatory (AO) meteor observations of what we have termed "radar bolides". These events appear to be generated by larger and/or more energetic than average HPLA (High-Power, Large-Aperture) radar-accessible meteoroids that have reached ~90 km altitude and that are fragmenting and flaring [1,5]. This update is timely as all-sky VHF imaging at the LWA1(Long Wavelength Array prototype radio astronomy imager) has firmly linked RF-emission "tracks" on the sky to the optical tracks of bolides as observed by several bolide cameras in New Mexico [2]. Obenberger et al. [2] refer to this phenomenon as meteor "afterglow" and convincingly demonstrate that these "afterglows" are emissions and not scattering from distant RF transmitter sources. While these RF-emission bolides are undoubtedly large compared with the AO events, they seem to offer insight into the AO events.

Figure 1. The Arecibo Observatory (AO) 430/46.8 MHz co-axial antenna feed system illuminating the 1000 ft diameter spherical-cap dish. This arrangement uniquely provides common-volume V/UHF results in the narrow UHF beam. The radar scattering physics at each frequency helps interpret the net meteor trail- and head-echo return. Note that the VHF radar is much less sensitive in Radar Quality Factor (RQF) terms than the UHF radar. System details are given in Table 1.

2. AO Radar Meteor Observations

The Arecibo Observatory (AO) geophysical radar co-axial feed system shown in Figure 1 allows very useful common-volume meteor studies at 430/46.8 MHz. The system parameters are given in Table 1 where we note that the 430 MHz radar is by far the most sensitive of the two systems. However, the wider beam—and thus larger-meteoroid event rate—and much larger wavelength together make the 46.8 MHz radar very useful for studying meteor head/trail/flare-echo scattering [6,7].

Table 1. Arecibo Radar Properties

Radar (MHz)	Beamwidth	Gain (dBi)	Power	System Temp (K)	RQF* (MW/K)
46.8	1.4˚	40	~40 kW	3000	~0.007**
430	0.17˚	61	~2 MW	100	~4295

*RQF=Transmitter Power(MW)×Aperture(λ^2)/System Temperature (K)

**This is approximately the RQF for a JRO 1/64th array receive module while transmitting on ¼-array.

We next discuss two unusual types of radar meteors observed at AO. Figure 2 shows three, possibly related radar meteor events as described in the caption. Event 2 appears to be a "fossil" radar bolide event that, we suggest, defines a new class of radar meteors. It is likely the remnant terminal flare plasma from a larger meteoroid for which the head-echo occurred outside of the beam.

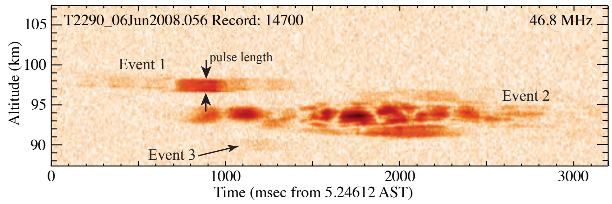

Figure 2. AO VHF radar Range-Time-Intensity (RTI) signature of a complex of meteor-related events that together pose a radio science and meteor/meteoroid conundrum. Event 1, if a single event, shows a faint head-echo and two flare-trails. Event 3 is likely a weak flare-trail. Event 2 appears to be a "fossil" radar bolide event that possibly defines a new class of radar meteors. None of these events were observed by the 430 MHz radar.

Figure 2, Event 2 lasted about 2 seconds with the longest lived of this event class lasting about 10 s. Note the complex fading—indicated by vertical structure shorter than the pulse length—between features at different ranges suggesting evolution due to parallel-B diffusion and/or flare-plasma structures along the trail. Long-lived events—likely due to (near) bolide-class meteoroids—such as these almost certainly involve dusty plasmas and are likely important to Mesosphere & Lower Thermosphere (MLT) electrodynamics as we discuss next. We further suggest that this meteor events category has certainly been seen by various D-region radar probing techniques such as MST and "classical" meteor radars all along but appear to have gone unrecognized or included in the "overdense" (aka unidentified) bin. For meteor plasma volumes small compared with a Fresnel zone, it is unlikely that true overdense scattering will occur [8,9]. We emphasize that meteoroid fragmentation will create complex head/trail-echo structures that may be attributed to overdense scattering [1,8,9].

The event shown in Figure 3 introduces a new radar meteor phenomenon, the *delayed-echo* feature associated with an intense meteoroid flaring event. We believe it likely that the flare intensity bespeaks a larger, more energetic meteoroid such as those that generate the Figure 2 radar-bolide-like events but in this case we observe the head-echo event and the flare rather than the remnant(s).

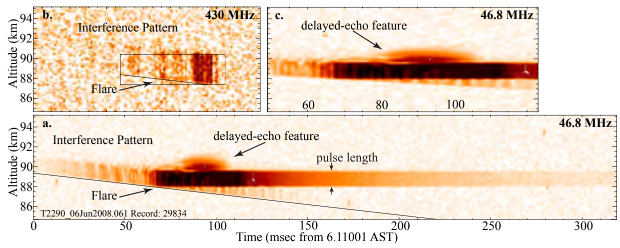

Figure 3. A low-altitude AO V/UHF meteor with fragmentation and flaring. (a.) The VHF head-echo shows simple fragmentation structuring (interference pattern) with a strong flare-echo at 67 msec and unusual additional scattering feature, the *delayed-echo*, that appears only after the flare but at greater range. (b.) The corresponding UHF event is much weaker (it is likely in the sidelobes) with no indication of a flare-echo but it does indicate fragmentation. Note that the time scale is the same as in panel (a.). (c.) The time-expanded view of the flare clearly showing the *delayed-echo* associated with the intense flare event. The head-echo line-of-sight speed of this event is ~21.8 km/sec.

The Figure 3 *delayed-echo* meteor event is the most striking example of this phenomenon we have observed to this point. However, these *delayed-echo* events are

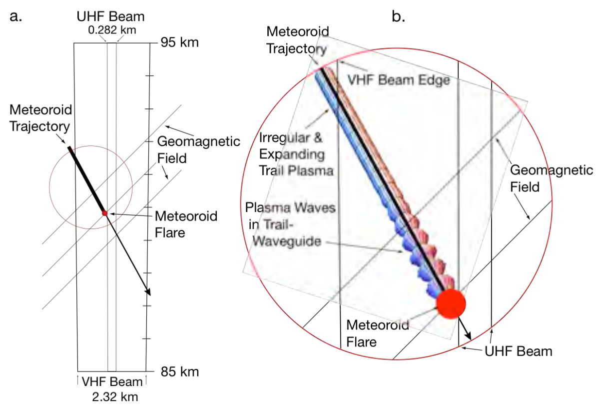

Figure 4. Proposed *delayed-echo* event geometry. (a.) A meteoroid trajectory showing a fragmentation flare. We depict the trail-plasma before the flare as being denser than after the flare as seems likely. (b.) The "exploded" view shows the flare that, we hypothesize, launches an intense Langmuir wave back along the dense but (irregularly) expanding trail-plasma that acts as a channel or waveguide. The wave feature shown is meant solely to indicate compressional waves and not the wave physics.

observed a few times per hour in the pre-dawn hours. The meteor *delayed-echo* seems to point to "wave" and/or electrodynamic process(es) that propagate away from the flare-origin at ~50-100 km/sec. A schematic of our proposed event geometry is shown in Figure 4.

Note that in Figure 4b, the wave-like feature depicted is meant solely to emphasize the presence of compressional "waves" in large transverse plasma gradients and not actual waves. In this scenario the observed *delayed-echo* originates from a few high-gradient features likely sharpened by the breaking Langmuir waves. That there are only a few scattering features seems evident from the mild vertical interference pattern seen in Figure 3. Note that many scattering features would tend to scatter incoherently and thus become invisible to the weak VHF radar.

3. Implications of RF Bolide Signatures

While the *delayed-echo* meteoroid flare feature shown in Fig. 3 is intrinsically interesting, it is difficult to proceed without corroborative evidence of some sort. It appears that recent all-sky imaging observations at the prototype Long-Wavelength Array (LWA1) located at the VLA near Socorro NM have compellingly revealed VHF emissions from along the trajectory of optical bolides [2 and references therein] as observed by a network of bolide

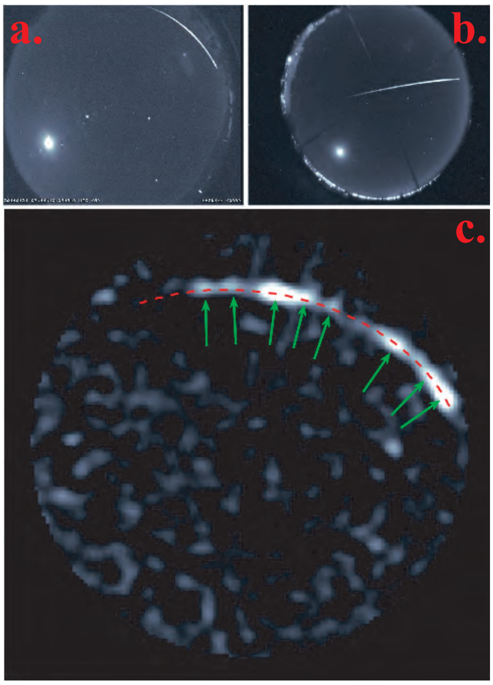

Figure 5. Figure 1 of Obenberger et al. [2]. Frames (a.,b.) show the full trajectory of an optical fireball as seen by two widely separated bolide "patrol" video camera systems in New Mexico. (c.) The LWA1 all-sky VHF (~38 MHz) image constructed for the ~15 sec period of the optical bolide. This image shows the bolide RF "afterglow" with the dashed line showing the optical trajectory of the bolide and the arrows indicating RF features for which the altitude was derived from the optical trajectories. See [2] for observational details.
camera systems. These RF emissions are attributed to bolide-generated plasma waves with incumbent mode conversion to VHF emissions.

The Figure 5c LWA1 image was obtained using the LWA PASI (Prototype All-Sky Imager) backend with a total of 154 transient events attributed to bolides observed since 2012. The bolide camera systems recorded 1382 bright meteors over 2012-2013. Of course the camera systems only function at night under good seeing conditions. The PASI backend was apparently used over much if not all of this period.

While the Figure 5 images from Obenberger et al. [2] are compelling, their altitude distribution of the RF afterglows given in Figure 6 is additionally so. In particular, the optical bolide altitude distribution is derived from the 1382 events observed by two NASA/MEO (Meteoroid Environment Office) all-sky video systems in 2012-2013. The afterglow event altitude distribution is derived from 44 events for which triangulation yielded 76 distinct altitudes for RF "hotspots" on the LWA1 trajectories. These results show a sharp decrease in afterglow events below 90 km altitude that can be interpreted in terms of suppression of excitation and/or propagation of Langmuir waves. That the altitude distribution above 90 km closely follows the bolide altitude distribution bears further attention.

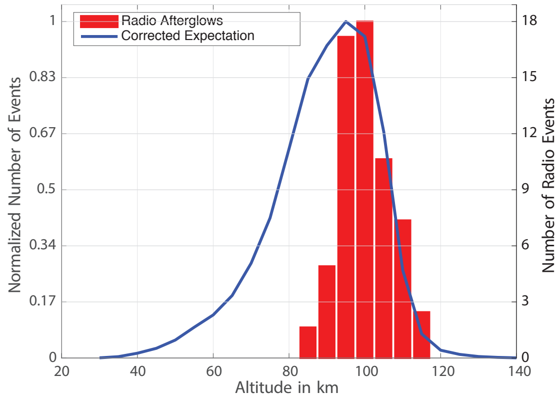

Figure 6. Figure 3 of Obenberger et al. [2]. Shown are the normalized altitude distribution of observed bright camera meteors (blue) as contrasted with the LWA1-derived altitude distribution of radio "afterglows" (red). The altitude of VLA1 bolide "afterglows" was derived from camera triangulation and the azimuth/elevation of the corresponding VLA1 afterglow "pixel". The altitude bin size of 5 km matches the typical amount of AZ/EL error in the "on-sky" position measurements. Note that above 90 km the measured distribution of radio events closely matches that of the optical bolides. However, below 90 km the number of RF-afterglow events drops off much faster than expected from the optical events. This suggests a strong altitudinal dependence of the radio emission mechanism.

4. Conclusions

As observed with the AO VHF LPLA (low-power, large-aperture) radar, we identify two new classes of radar meteor events. The first includes complex, long-lived (~1-10 sec) echoes for which the head-/flare-echoes are not observed as they apparently occur outside of the radar beam. The second new class of meteors are seen as complex (fragmenting) head-echoes that also exhibit intense meteoroid flaring that gives rise to *delayed-echoes*. In both cases the progenitor meteoroid is assumed to be relatively large and energetic as the associated radar meteors have very unusual features and are observed deep in the atmosphere. We suggest that both event classes can be identified as "radar bolides".

The first class of radar bolides—for which head-echos are not observed—is relatively common and identified with long-lived ($\lesssim$10 sec) echoes are seen with the AO LPLA VHF radar. That these echoes survive against parallel-B diffusion and recombination likely points to dusty plasma given the AO ~45° dip angle at 90 km altitude. These are likely "fossil" radar-bolide trails or flares with the head-echoing region not observed having, we assume, occurred outside the beam. At geomagnetic equator location of Jicamarca Radio Observatory, FAI (Field-Aligned Irregularity) scattering masks these events as nearly all meteors in the radar $\mathbf{k} \perp \mathbf{B}$ region display long-lived flare and range-spread trail-echoes (RSTEs) [10]. RSTEs are observed with the AO LPLA VHF radar but are short-lived due to rapid parallel-B diffusion.

Energetic meteoroid flaring sometimes generates *delayed-echoes* observed by the AO VHF radar. We suggest that intense "breaking" plasma (Langmuir) waves propagating away from the flare point along the trail "waveguide" generate the additional scattering features in the plasma.

The LWA1 RF emission observations associated with optical-bolides [2 and references therein] are, we suggest, likely related to the meteoroid flare *delayed-echoes* observed at AO. We further suggest that the RF signature originates from the currents in large electron concentration gradients where the Langmuir waves "break". We have not observed RF emissions in AO/JRO meteor events but we are now looking for them.

Finally, we note that the MMF (Meteoroid Mass Flux) is multi-scale. Even single meteoroid entry events appear to be electrodynamically important as is the collective MMF. "Radar bolides" reveal interesting clues to the plasma dynamics and electrodynamics of the mesopause region. The MMF constitutes a global, non-solar space weather system.

5. Acknowledgements

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6. References

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