Association Between Meteor Radio Afterglows and Optical Persistent Trains

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Abstract This paper presents the first observed association between meteor radio afterglows (MRAs) and persistent trains (PTs) and provides the first evidence of a link between these two phenomena. Co-observations of four meteor trails (trains) from the Long Wavelength Array (LWA) telescopes in New Mexico and the Widefield Persistent Train (WiPT) camera associate the long-lasting (tens of seconds), self-generated radio emission known as MRAs with the long-lasting (tens of minutes) optical emissions known as PTs. Each of the four MRAs presented in this paper were spatially and temporally coincident with a PT. In one case, the MRA follows a relatively small (<400 m × 400 m) noticeably bright region (knot) of emission within the PT, whereas the other three cases were associated with broader regions of PT activity. As PTs are thought to be driven by exothermic chemical reactions between atmospheric oxygen and ablation products, we show that the same reactions, specifically those involving anions, may produce the necessary suprathermal electrons to power MRAs. We show that only one part in ~1010 of the available power needs to be converted to radio emission in order to produce a typical MRA.

1. Introduction

The plasma trails of some, typically visibly bright, meteors have been observed to produce a radio afterglow in the high frequency (HF; 3–30 MHz) and very high frequency (VHF; 30–300 MHz) bands (Obenberger et al., 2014). These meteor radio afterglows (MRAs) are characterized by a broad and smooth spectrum covering at least the 20 to 60 MHz frequency range and lasting from tens of seconds up to a few minutes (Obenberger, Taylor, Lin, et al., 2015; Obenberger, Dowell, et al., 2016). Furthermore, Obenberger, Homes, et al. (2016) showed that MRAs have a strong altitude cutoff at ∼90 km, below which MRAs are not observed. The emission from MRAs has also been found to be nearly isotropic (Varghese et al., 2019). Despite these extensive studies the mechanism by which MRAs radiate is still a mystery.

Previous studies have noted that the radiated frequencies closely match the range of plasma frequencies that are expected in the trails of large meteors. One possible mechanism of creating emission at these frequencies is through the electromagnetic conversion of electrostatic plasma waves such as Langmuir waves. However, these waves would require an instability to be present in the meteor trail plasma. Oppenheim and Dimant (2016) showed photoelectrons produced by ionizing radiation from the Sun could produce a bump-on-tail instability and induce Langmuir waves in the daytime ionosphere at altitudes of 150 km. This mechanism may explain the 150 km radar echoes often seen at equatorial latitudes. However, photoelectrons cannot be the main driving force for MRAs since they occur both at night and during the day.

Another possible emission mechanism is transition radiation (TR), where hot electrons, moving at a constant velocity through an inhomogeneous plasma, radiate due to the changing refractive index of the plasma (Platonov & Fleishman, 2002). The spectra of TR has a sharp peak near the local plasma frequency where it is often referred to as resonant transition radiation (RTR). Similar to a plasma wave instability, RTR requires a spectrum of suprathermal electrons, but electrons kicked off in the initial ablation/ionization process would likely thermalize much faster than the typical time scale of MRAs.

In similar fashion to MRAs, meteor trails (or trains) have also been known to occasionally produce long-lasting visible (Trowbridge, 1907) and infrared (Hapgood, 1980) emission, typically referred to as a persistent train (PT, see Borovicka, 2006 for an overview). Not to be confused with smoke trails, which scatter sunlight shortly after sunset or before sunrise, PTs are self emitting. PTs are considered to be relatively rare...
and to occur only during bright, fast meteors. Although, this information is based on limited studies carried out during the periods of high Leonid activity of the late 1990s and early 2000s (Drummond, Grime, et al., 2001; Drummond, Milster, et al., 2001; Drummond et al., 2002; Higa et al., 2005; Kelley et al., 2000, 2003; Kruschwitz et al., 2001; Toda et al., 2004; Zinn & Drummond, 2005).

The visible and NIR emission of PTs is thought to be powered by continuous, exothermic chemical reactions occurring between the ablated meteoric materials and atmospheric oxygen molecules (Chapman, 1955; Clemesha et al., 2001; Kruschwitz et al., 2001). We hypothesize that these same types of reactions could be a potential source of suprathermal electrons that could also drive MRAs. Of particular interest are reactions involving negatively charged metal ions (anions), which may kick off electrons with a few eV of energy. A simple test of this hypothesis would be to search for a spatial and temporal correlation between MRAs and PTs. If a correlation is found, then it is possible that the two phenomena share the same energy source.

In this paper, we present coincident optical and radio observations of four MRAs. The following sections are organized as follows: Section 2 introduces a hypothetical framework for chemically produced suprathermal electrons, section 3 describes our observations, section 4 details our analysis steps, section 5 discusses our findings, and section 6 provides a conclusion.

2. Chemically Produced Suprathermal Electrons

MRAs have been associated with high velocity (>40 km/s), large (~10 g) meteoroids (Obenberger, Homes, et al., 2016; Obenberger et al., 2014). During atmospheric entry, this class of meteor is likely to ablate a wide variety of metals into atomic species and clusters, but mostly involving the abundant Fe and Mg elements (Borovicka & Jenniskens, 2000; Madiedo et al., 2014; Masib, 1971; Plane et al., 2015). The exact distribution of particles is not vital to the present work as we simply mean to test the plausibility of ablated species resulting in enough suprathermal electrons to account for observations.

It has been shown numerous times (e.g., see Shuman et al., 2015 for a review and Kelley, 2004 for a rocket-based experiment) that particles left over from ablation can attach electrons and form negative ions, which have been observed but not identified. Here we give a rough estimate that shows that attachment to ablated particles (AP), which should be similar but not the same as meteoric smoke particles Hunten et al. (1980), and subsequent reaction with oxygen can produce the hot electrons that could explain the observed MRA emissions. While the exact chemistry has never been measured, we propose that surrogate reactions give a reasonable estimate of the rate constants involved.

The proposed chemistry is straightforward and starts with electron attachment to ablated particles,

\[ e^- + AP_1 \rightarrow AP_2^- \]  

where \( AP_1 \) and \( AP_2^- \) may or may not have the same composition; i.e. it does not matter whether the negative ion is the same mass as the original particle from associative attachment, or is a result of dissociative electron attachment. It is difficult to study attachment to these APs given the wide variety of species likely and the difficulty of getting them into the gas phase. However, both pure and mixed metal particles commonly attach electrons in laser vaporization sources (Duncan, 2012). The best surrogate available to estimate a quantified rate constant is \( C_{60} \), which has an attachment rate constant of \( 10^{-6} \text{ cm}^3 \text{ s}^{-1} \) (Viggiano et al., 2010). A wide distribution of negative ions would be expected, some of which may be oxidized to some extent. Hot electrons are subsequently produced by detachment in reaction with O or \( O_2^- \),

\[ AP_2^- + O_n \rightarrow e^- + AP_3 + X \]  

In this case, \( AP_2^- \) and \( AP_3 \) are expected to have different masses as explained below. We have previously published data for \( Al_{6n}^- \) clusters undergoing such reactivity (Sweeney et al., 2019). Using the same technique, we present here data for heavier metals that react with a larger rate constant. Table 1 shows data for Reaction 2 for clusters of pure metals with 10 atoms each reacting with \( O_2^- \). Rate constants and the branching fraction-producing electrons are shown. We do not expect pure metals in the meteor trail but expect similar chemistry. The reactions we have studied, except for Al, react at or near the collisional limit and produce mainly or exclusively electrons. In our laboratory experiment, we often can detect electrons by scavenging them with \( SF_6 \), which efficiently attaches low-energy electrons. However, for V, Cr, Co, and Ni, little scavenging occurred even though it was clear that electrons were produced since the total number of ions decreased.
and the current to the nose cone went to near zero at high O$_2$ flows. The only explanation for these observations is that high-energy electrons are produced which both increased the diffusion rate and decreased the attachment rate. Likely, the mechanism produces a broad range of electron energies, with the approximate maximum value for clusters of a single metal estimated in Table 1. From this it is reasonable to expect that the APs in the trails, although they will be of mixed metal content, would also have large rate constants and produce mainly electrons. Partial oxidation should not change the chemistry considerably, for example, a small number of oxygen atoms in a large cluster will behave more like a pure metal than an oxide, though eventually, full oxidation may render the anions inert.

To estimate the amount of charge in the form of negative anions, we can assume a steady state and equate the production and loss rates of electrons in Reactions 1 and 2. For practicality, we group all APs into a single species and consider only O$_2$, which is significantly more abundant at heights where meteors ablate, though a large amount of dissociated O is expected in the immediate trail. The chemistry with atomic O is expected to be similarly fast and potentially results in even higher energy $e^-$. Assuming steady state between Reactions 1 and 2 yields, 

$$\frac{[AP^-]}{[AP]} = \frac{k_1[e^-]}{k_2[O_2]}, \tag{3}$$

where $[n]$ is the number density of species $n$. Substituting the electron density as $10^9$ cm$^{-3}$, the attachment rate as $10^{-6}$ cm$^3$ s$^{-1}$ ($k_1$), the detachment rate ($k_2$) as $5 \times 10^{-10}$ cm$^3$ s$^{-1}$ (from Table 1), and a typical O$_2$ density at 100 km as $2 \times 10^{12}$ cm$^{-3}$ (Schunk & Nagy, 2009) one finds about 10% of the APs are ionized. Finally, we can substitute that into the rate equation for production of potentially hot electrons,  

$$d[e^-]/dt = k_1[AP^-][O_2] \tag{4}$$

As MRA emissions are observed for larger meteors, we conservatively estimate [AP] from calculations of particle concentrations in the trail of a 6 g meteoroid by Öpik (1958) as $1.07 \times 10^{12}$ particles/cm$^3$. Rosinski and Snow (1961) estimated aggregation of these particles into meteoric smoke particles (MSP) yielding a concentration of $\sim 10^8$ 1-nm diameter particles per cm$^3$ after a duration of 1.8 s in the trail of a 6 g meteor. As MSP formation, diffusion, and other chemistries will compete with the present model, we conservatively take [AP] as $10^{10}$ particles/cm$^3$. Equation 4 then yields a rate of electron production of $\sim 10^{17}$ cm$^{-3}$ s$^{-1}$ assuming $k_1$ as above, $[O_2]$ as above, and [AP$^-$] from Equation 3 as $\sim 10^9$ cm$^{-3}$. Assuming an average electron energy of 1 eV and a trail radius of 15 m (line density of $\sim 10^{15}$ cm$^{-1}$) and a length of 10 km (beam size of LWA), the hot electrons approximated would provide roughly $10^6$ W of power in a single LWA beam. Assuming an MRA spectral shape similar to those measured in (Obenberger, Dowell, et al., 2016) with a hypothetical sharp turnover at 15 MHz, a typical MRA has a peak bandwidth-integrated power of roughly $10^{-4}$ W per beam. While most of the energy from the hot electrons would go into heating of the ambient atmosphere, it is certainly plausible that $10^{-10}$ of the available energy could be converted into radio emission. This approximation is coarse as the multitude of species and chemistries is simplified; however, 10 orders of magnitude of headroom show that this model is plausible.

The lifetime of the MRAs would be affected by diffusion of electrons, the rate of aggregation into MSPs, and the time scale of complete oxidation of a particle’s surface such that Equation 2 cannot occur and that particles no longer contribute to the suprathermal electron density. As the APs become completely oxidized, reaction with O atoms can similarly produce hot electrons.

| Metal cluster | $k_{300K}$ (cm$^3$ s$^{-1}$) | $\% \ e^-$ | $E_{\text{max}}$ (eV) |
|---------------|-----------------|---------|-----------------|
| Al$^{+10}$    | $1.9 \times 10^{-11}$ | 40      | $\sim 7$       |
| V$^{-10}$     | $5.1 \times 10^{-10}$ | 100    | $\sim 9$       |
| Cr$^{-10}$    | $3 \times 10^{-10}$ | 100    | $\sim 6$       |
| Fe$^{+10}$    | —                | —      | $\sim 4$       |
| Co$^{-10}$    | $3.3 \times 10^{-10}$ | 100    | $\sim 2$       |
| Ni$^{+10}$    | $3 \times 10^{-10}$ | 60     | $\sim 1$       |
Table 2
MRA/PT Times and Solar Elevation Angles

| Event name | Date     | UT   | MST   | $\phi_S$ |
|------------|----------|------|-------|----------|
| MRA1/PT1   | 2/3/2019 | 11:03| 04:03 | $-37^\circ$ |
| MRA2/PT2   | 12/2/2019| 08:27| 01:27 | $-67^\circ$ |
| MRA3/PT3   | 12/2/2019| 11:57| 04:57 | $-25^\circ$ |
| MRA4/PT4   | 12/18/2019| 05:50| 22:50 | $-71^\circ$ |

Note. Date is formatted as month/day/year.

3. Observations

Currently there are two Long Wavelength Array (LWA) radio telescopes in central New Mexico. The first (LWA1) is located near the town of Magdalena, NM (Ellingson et al., 2013) and the second is located at Sevilleta National Wildlife Refuge (LWA-SV; Cranmer et al., 2017). Each telescope consists of 256 dual-polarization dipole antennas arranged pseudo-randomly across a $100 \times 110$ m ellipse and is capable of observing in the lower VHF and upper HF bands. Both are equipped with a LWA All-Sky Imager (LASI; Obenberger, Taylor, Hartman, et al., 2015) back end, which correlates a live stream of 100 kHz from each antenna and continuously produces 5-s snapshots of the entire sky in near-real time. LASI can be tuned to any frequency in the LWA frequency range (10–88 MHz for LWA1 and 3–88 MHz for LWA-SV), but they are typically tuned to 38 MHz. The synthesized full width at half maximum (FWHM) beam size of each LWA station at 38 MHz is $\sim 4.5^\circ$ at zenith; however, for point sources with high SNR a much higher level of position accuracy is attainable. The LASI images from each station are stored to a permanent archive, they can be accessed at this site (http://lda10g.alliance.unm.edu).

In addition to LASI, LWA-SV has a GPU-based broadband correlator and imaging system that is capable of imaging the entire sky with up to 19.8 MHz of bandwidth on time scales of 5 s. With $\approx 200$ times the bandwidth of LASI this imaging system is up to 14 times more sensitive (since the sensitivity scales with the square root of the bandwidth). However, with 200 times as much data, continuous recording of 5-s integrations has only recently become viable.

The Widefield Persistent Train camera (WiPT) was deployed to LWA-SV from 19 September 2018 to 4 February 2019 and again from 19 November 2019 to 20 December 2019. WiPT consists of a Canon 15 mm f/2.8 fisheye lens, which is mounted on an Apogee Alta F9000 cooled CCD camera system. The F9000 is capable of cooling to $-40^\circ$C below the ambient temperature and is equipped with a Kodak KAF-09000 sensor, which consists of a $3,056 \times 3,056$ array of $12 \times 12$ $\mu$m pixels. With a 51.9 mm diagonal, nearly the entire image from the fish-eye lens is captured by the sensor. Without any filter, the camera is highly sensitive to the later portion of persistent trains, which is broadband and has peaks in the lower visible and near infrared (NIR; Borovicka, 2006). The camera is programed to take a 5-s exposure, every 6.3 s during moonless, nighttime conditions. A typical stellar calibration places the image noise at about an apparent magnitude of 10, but this depends on the region of the sky and atmospheric conditions.

To date there have been four MRAs that have occurred while WiPT was operating and the sky was clear. The first (MRA1) occurred on 3 February 2019, the second (MRA2) and third (MRA3) occurred on 2 December 2019, and the fourth on 18 December 2019. While all four MRAs were detected by LWA-SV, LWA1 only detected MRA3 and MRA4. In the case of the MRA2, LWA1 was not operating in the all-sky mode at that time, and MRA1 was too far to the northeast and too dim to be observable by LWA1, which is located 75 km southwest of LWA-SV.

In each case, the MRA was accompanied by a PT (PT1, PT2, PT3, and PT4). For each, the Sun was too far below the horizon for there to be any scattered sunlight; therefore, each PT must have been self luminous. For an altitude of 100 km, the horizon is at $-10.1^\circ$, which was well above the solar elevation angle ($\phi_S$) at the time of each event. Table 2 provides the date, Universal Time (UT), Mountain Standard Time (MST), and $\phi_S$ for each MRA/PT event.

For the observing periods of 19 September 2018 to 4 February 2019 and 19 November 2019 to 20 December 2019, these four events were the only MRAs that occurred on a clear, moonless night, and therefore were the only opportunity for this study. The Andor F9000 that comprises the WiPT camera has suffered from
Figure 1. Zoomed-in radio images from each of the four MRAs: (top left) MRA1; (top right) MRA2; (bottom left) MRA3; (bottom right) MRA4. Each image is roughly 25° × 25°. As can be seen, only MRA1 appears as a point source, the others all appear extended.

a sticky shutter, which is why the observing periods ended when they did. Currently, the camera is being replaced by the authors, who hope to redeploy sometime in 2020.

4. Analysis

Absolute power calibration of LWA images was carried out using the radio source Cygnus A in the same manner as described in (Obenberger, Taylor, Hartman, et al., 2015). The meteor radio afterglows (MRAs) were detected using the pipelines described in (Obenberger, Taylor, Hartman, et al., 2015) and (Varghese et al., 2019), where LASI images are processed using an image subtraction algorithm in order to identify transient events. Once an MRA was identified, we then analyzed the data from the broadband imager at LWA-SV, which allows us to increase the signal-to-noise ratio and achieve the best possible positioning. With MRAs identified we could then also search the widefield persistent train (WiPT) camera images for optical PT counterparts. We note that while current LWA broadband imager observations capture 20 MHz bandwidth with 5-s integrations, at the time of MRA1, the broadband imager was only operating at 10 MHz bandwidth, with 10-s integrations.

Each WiPT image is full of sources such as stars, airglow, and anthropological light pollution, all of which interfere with the PT identification. To mitigate this, we subtract from each image the previous day's image, which occurred at the same local sidereal time (LST). These processes remove some of the anthropological light pollution and most of the stellar emission, leaving a residual due to differences in LST on the order of the 6.3-s duty cycle. From these subtracted images, it was relatively easy to identify a meteor and then subsequent PT by eye using a sequence of images played in a movie. Each of the four PTs described in this paper was found this way. While image subtraction was adequate for displaying PT2, the other three benefited from two-dimensional Fourier filtering, where we applied a Gaussian high pass filter. This filtering removed much of the structured airglow and other light pollution that was present during these events.
Figure 2. Radio frequency light curves from each of the four MRAs, made using the LWA broadband imager, where flux density is measured in Jy. The time axis is set relative to the moment the optical camera first detected the meteor.

While MRA1 was observed to be a point source, the other three were all resolved by LWA-SV to be elongated. MRA3 was resolved to be elongated from start to finish, but MRA2 and MRA4 only initially appeared elongated. As the MRAs dimmed, their angular sizes decreased, each becoming point-like after a few tens of seconds. Since MRA1 was observed to be a point source, we were able to model the centroid PSF of the image to attain superresolution after image subtraction with a positional precision of $\sim 0.1^\circ$, which is about the size of a single WiPT pixel. Figure 1 shows the zoomed-in images of each MRA for comparison, and only MRA1 can be characterized as a point source.

The light curve of MRA1 also stood out in that it had a relatively long rise time when compared to the others. These features are evident in Figure 2, which shows the radio light curves for each of the MRAs, with $t=0$ at the point where the optical camera first detected the respective meteor. This variability between MRA

Figure 3. Fish-eye image taken with the WiPT camera at the moment the meteor first appeared; also shown is an inset close-up of the meteor. In both images the initial position of MRA1 is shown by the red circle. Light pollution from Albuquerque can be seen to the northeast, and atmospheric airglow can be seen as large banded structures across the image. Pixel streaks from bright stars can also be seen due to the faulty shutter on the Andor F9000. Included in the bottom left corner of each image is a white circle the approximate size of a LASI synthesized beam at 38 MHz.
features is common, but is certainly worth noting as the source of this variability is currently unknown. The following subsections deals with the comparisons between the MRA and PT for each event.

### 4.1. MRA1/PT1

Figure 3 shows the optical fisheye view from the integration the meteor first appeared, with a closeup inset showing finer detail. This meteor produced both a PT, which lasted \( \sim 10 \) and half minutes, as well as a MRA, which lasted \( \sim 50 \) seconds and appeared as a point source to LWA-SV. Figure 3 also shows a red circle where the MRA was first detected.

PT1 contained a significant amount of structure, which evolved gradually with time. While the trail was initially linear, a variety of wind speeds and directions as a function of altitude made PT1 increasingly convoluted with time. A video showing the evolution of PT1 is included in the supporting information. While the video only shows the first 6 min, PT1 lasts for a total of roughly 10.5 min before it dims to the point of being undetectable.

Figure 4 shows five snapshots of PT1, showing the evolution with time. Overlaid on these images are the corresponding positions of MRA1, which were derived using a 2-D Gaussian fit to the broadband imager data. WiPT has a duty cycle of 6.4 s, whereas at this time, the broadband imager has a duty cycle of 10 s. The optical image shown in each panel corresponds to the nearest image to the MRA measurement. From these five images it is clear that MRA1 is following a particular region of the PT. Using nearby stars to calibrate, we estimate that 12.6 s after the meteor ablates the \( \sim 2^\circ \) region of PT1 centered on MRA1 has an apparent magnitude of \( \sim 8.3 \).

The sixth image in Figure 4, shows the maximum pixel value for 26 consecutive snapshots (170 s) starting with when the meteor first appeared. This image is overlaid with the five consecutive measurements of the MRA location. It is clear from this image that MRA1 follows a particularly bright line which extends to the southeast. This line indicates that a small, noticeably bright region (knot) of emission is drifting in that direction. The knot appears to be the size of a single WiPT pixel, making it no larger than \( \sim 400 \text{ m} \times 400 \text{ m} \).

We note that the knot is not the brightest region of the trail, rather it is only brighter than the immediate surroundings, and there are other brighter regions of the PT that did not produce MRA emission.
We can track the bright knot in PT1 for several minutes, and doing so we can get an estimate of the velocity. From a single measurement location, we are unable to triangulate the height of the knot/MRA. However, we can assume the MRA is within the height range of 90–110 km (Obenberger, Homes, et al., 2016). Assuming a probable height of 100 km, we can project the optical measurements onto east north up (ENU) coordinates. Assuming there is no vertical wind component and that the path of the knot is in a straight line, we can fit a line to the east and north positions with time. Using 17 consecutive points (∼2 min), we fit the eastern speed to 138.6 m/s with a 95% confidence bound of ±2.7 m/s and a coefficient of determination ($R^2$) of 0.9987 and a northern speed of 36.3 m/s with a 95% confidence bound of ±4.8 m/s and a $R^2$ of 0.9452. Figure 5 plots these measured positions along with the linear fit, and as can be seen, the fits are well within ±1 pixel of the measurements.

The knot’s combined east and north speed of 143.3 m/s is far higher than the speed predicted by the Horizontal Wind Model 2014 (Drob et al., 2015), which predicts a maximum wind speed of 58 m/s in the altitude range of 90–110 km. Even when we consider the ∼10% error associated with the unknown height, the estimated velocity far exceeds the prediction. However, such wind speeds are often observed experimentally, for instance, by meteor radars (Oppenheim et al., 2014) and rocket experiments (Larsen, 2002).

4.2. MRA2/PT2

MRA2 lasted for ~50 s and was initially resolved by LWA-SV to be elongated. The accompanying PT, PT2, lasted for 4 min. PT2 occurred on only a portion of the initial meteor trail, and this activity does not appear to be correlated with optical features of the main meteor entry event. As PT2 evolves the wind pushes the
Figure 6. Five consecutive optical images showing PT2 at 5 s (top left), 10 s (top middle), 15 s (top right), 20 s (bottom left), and 25 s (bottom middle) overlaid with half-maximum contours of MRA2, taken from LWA broadband images from the same moments. The sixth panel (bottom right) shows the maximum pixel from each image over the entire duration (4 min) of PT2 and is overlaid with a half-maximum contour of MRA2, averaged over its duration (50 s).

Figure 6 shows a five-image sequence of PT2, where each image is overlaid with half-maximum contours from the elongated MRA2. Unlike MRA1, MRA2 does not appear to be associated with a single fast moving knot. Rather it appears to be coming from an extended region of PT activity. This region of PT2 contains a variety of velocities, generally moving to the southwest. MRA2, on the other hand, does not appear to be moving with the fastest component, and as MRA2 dims, it centers on an almost stationary region of PT2. The sixth panel of Figure 6 shows the maximum pixel value from the entire duration of PT2, highlighting the brightest components of PT2 smeared to the southwest of the initial meteor trail. This image is overlaid with a half-maximum contour of MRA2, averaged over its duration. We note that for a point source, the half-maximum is approximately the beam size shown in Figures 3 and 4.

Similar to PT1 we can calibrate PT2 using nearby stars. We estimate that two integrations (12.6 s) after the meteor ablates, PT2 has an average apparent magnitude of \( \sim 8.1 \). We note that while our calibration estimates that PT2 is actually brighter than PT1, PT2 appears to be considerably dimmer than PT1 when comparing Figures 4 and 6. This discrepancy is likely due to different atmospheric conditions on each night.

4.3. MRA3/PT3

MRA3 lasted for \( \sim 30 \) s and was resolved by both LWA-SV and LWA1 to be elongated for its entire duration. PT3 was widespread across most of the ablated trail, but there is clearly a bright region. We note that the optical brightness of PT3 does not appear correlated with optical features of the main meteor entry event. A westerly wind pushes PT3 to the east. The exact duration that PT3 is observable is not known as the observations ended while PT3 was occurring. A video showing the first 3 min of PT3 is included in the supporting information.

Figure 7 shows a five-image sequence of PT3 overlaid with half-maximum contours from the elongated MRA3. From this figure, it is clear that the bright region of PT3 is colocated with MRA3. The sixth panel of Figure 7 shows the maximum pixel from 31 consecutive images (\( \sim 3 \) min). This image reveals that the bright region, which is colocated with MRA3, is composed of several knots of emission traveling generally east. Again using nearby stars to calibrate, we estimate that two integrations (12.6 s) after the meteor ablates in
Figure 7. Five consecutive optical images showing PT3 at 5 s (top left), 10 s (top middle), 15 s (top right), 20 s (bottom left), and 25 s (bottom middle) overlaid with half-maximum contours of MRA3, taken from LWA broadband images from the same moments. The sixth panel (bottom right) shows the maximum pixel from each image over the entire measurement (3 min) of PT3 and is overlaid with a half-maximum contour of MRA3, averaged over its duration (30 s).

this region of PT3 has an apparent magnitude of \( \sim 8.6 \). While initially dim, it can be seen in Figure 7 that the knots increase in brightness as they evolve.

Since MRA3 was observed by both LWA-SV and LWA1 we are able to triangulate its position. The fact that MRA3 is elongated enables us to get a latitude, longitude, and altitude for both the upper and lower portions of the radio emission. The highest region occurred at 34.21°N, 107.69°W, and 107.02 km, whereas the lowest region occurred at 34.42°N, 107.61°W, and 98.64 km. This indicates a rather shallow angle of incidence of \( \sim 20° \) relative to the tangent of Earth’s surface.

4.4. MRA4/PT4

With a duration of 80 s, MRA4 lasted the longest of the MRAs reported in this paper, and it was resolved by both LWA-SV and LWA1 to initially be elongated. However, the accompanying PT, PT4, was the poorest detection of all the PTs, and this was likely caused by three factors: (1) There was increased image noise because the CCD cooler was malfunctioning and could only cool to \( \sim 0°C \); (2) with an apparent magnitude of \( \sim 9.2 \), PT4 was considerably dimmer than the others; and (3) the Moon rose while PT4 was still occurring, adding atmospheric scattered moonlight. These factors made PT4 difficult to measure and display graphically.

Since the WiPT camera is scheduled to cease imaging when the Moon rises, we cannot say for certain how long PT4 lasted, but it was present for the entire 8.5 min before moonrise. A video of the first 6 min of PT4 is included in the supporting information. The meteor that caused MRA4/PT4 began its entry right when a WiPT integration was ending, so most of the initial meteor was missed. However, since the beginning of the meteor was captured, we can get a lower estimate of the length of the trail assuming the PT occurred at the lowest portion.

PT4 was only present on about half (or less) of the initial meteor trail, and MRA4 occurred only in the region where PT4 was present. While PT4 was too dim to present effectively in a paneled image, the PT moved slowly enough to enable integration of the first four images (\( \sim 25 s \)) to get a higher SNR image of the PT. Figure 8 shows the four image average of PT4 overlaid with the half-maximum contour of the average of the first 25 s of MRA4. From Figure 8 it is clear that MRA4 is coming from the same region as PT4.
MRA4 was measured by both LWA-SV and LWA1 enabling triangulation of both the upper and lower portions of the trail. The lowest region occurred at 33.87°N, 107.56°W, and 93.88 km, whereas the highest region occurred at 33.79°N, 107.43°W, and 99.03 km. Similar to MRA3 these coordinates indicate a rather shallow angle of incidence of ∼18.5° relative to the tangent of Earth’s surface.

5. Discussion

In section 2, we outlined a possible mechanism where oxidation of negatively charged clusters of ablation products can produce a supply of suprathermal electrons. While oxidation reactions of both charged and neutral metals are thought to drive persistent trains (PTs), the hot electrons produced in anion reactions may provide the energy to meteor radio afterglows (MRAs). Association between MRAs and PTs would be the first evidence of such a mechanism, and the observations presented in this paper show that all four MRAs, occurring during the WiPT camera operation, were spatially and temporally coincident with a PT. These associations imply that chemical reactions are occurring coincidentally with MRAs, enabling the mechanism hypothesized in section 2 to be a viable energy source.

Structurally, MRA2, MRA3, and MRA4 show a broad region of radio emission coming from broad regions of PT2, PT3, and PT4. In particular the radio emission from MRA3 is centered on a relatively bright extended region of PT3. MRA1, on the other hand, appeared as a point source, with the radiating region being consistent with an optically bright knot within PT1. The optically bright regions associated with MRA1 and MRA3 may indicate a higher chemical reaction rate, higher density, or a more reactive composition.

While this study suggests that MRAs are accompanied by PTs, we should note that PTs are not always accompanied by MRAs. We used pipelines, described in Obenberger, Taylor, Hartman, et al. (2015) and Varghese et al. (2019), to find MRAs, which we then compared to images from the WiPT camera and found a PT for each MRA. While we have a pipeline to find meteors within the WiPT images, we have not yet developed a pipeline to identify PTs. We note however that by casually looking at bright meteors, we have found numerous PTs that do not have detected MRA counterparts.

As described in section 2 different metal oxides react at different energies. Therefore, it may not be surprising that not all PTs create a detectable MRA, as their chemical compositions vary. Moreover, Obenberger, Homes, et al. (2016) found strong correlation between the occurrence of MRAs and altitude, and at the time this relation was interpreted to mean that the neutral collision frequency of electrons was an important factor in determining whether or not an MRA could occur. However, the results of this paper may indicate that the altitude-dependent atmospheric abundances of O and O2 could effect reaction rates and play a significant factor in the energy spectrum. A future pipeline to detect PTs, will hopefully shed light on the percentage that are accompanied by MRAs, and spectral analysis may enable identification of the relevant reactions associated with MRAs, as well as PTs in general.

It is worth noting that the MRAs presented in this paper do not originate in the brightest region of their parent meteor. Rather, they are coincident with regions of PT activity. For example, Figure 3 shows that the meteor contains an extremely bright region, consistent with a flare, but this flare is not coincident with the location of the MRA. From the observations presented in this paper, we can infer that MRAs are more related to PTs than to flares. This is consistent with previous observations from Obenberger, Homes, et al. (2016) where ablation features seemed to be unrelated to MRAs. This is also consistent with the long durations of MRAs as compared to the optical flares.

Finally we note the lack of an apparent correlation between MRA flux density and apparent PT magnitude. Three of the MRAs had similar flux density, but the optical magnitude of their associated PTs varied greatly. This is expected given all of the factors which may be associated with MRA emission. Under the framework laid out in this paper, the brightness of an MRA would likely be related to the collision frequency, total available energy, electron energy spectrum, and the density structure of the plasma. Such a complicated
relation matrix is beyond the scope of this paper, but future studies would likely benefit from statistical analysis of a larger number of events.

6. Conclusion

We have presented data from four MRAs which clearly associate the radio emission with long-lasting optical emissions known as PTs. For each of the four cases, the radio emission is limited to regions where PT activity is observed. While this does not prove that these two phenomena are related, it at least provides strong evidence that they are. As PTs are thought to be driven by exothermic chemical reactions between atmospheric oxygen and ablation products, we suggest that the same reactions, specifically those involving anions, may produce the necessary suprathermal electrons to power MRAs.

Data Availability Statements

All of the LASI data used in this article are publicly available at the LWA Data Archive (http://lda10g.alliance.unm.edu), optical images can be found at this site (https://lda10g.alliance.unm.edu/~pasi/WiPT/), and broadband LWA data can be found at this site (https://lda10g.alliance.unm.edu/~pasi/Broadband/).

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