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Meteor Radio Afterglows: HF and VHF Radio Emission from Meteor Trails

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Abstract

The serendipitous discovery of broadband HF/VHF radio emission from meteor trails has opened a new door into observing meteors and raises new questions about meteor plasma physics. These transient events, referred to as meteor radio afterglows (MRAs), last for 10s to 100s of seconds after the ablation of a meteor, and only occur for meteors or portions thereof above $\sim$ 90 km. Light curves typically follow a fast rise and slow decay, and the spectra have been shown to follow a steep frequency dependent power law, getting brighter at lower frequencies. This discovery and further followup studies were made possible by advancements in many element HF/VHF radio telescopes, specifically the all-sky imaging capabilities of the LWA telescopes. In this paper we summarize the past and ongoing research on this new topic.

1 Background

In early 2014, Obenberger et al. [1] published two radio transients, one at 30 MHz and the other at 38 MHz. Each event had a light curve with a fast rise and exponential decay and lasted over a minute. It was later shown in [2] that these along with many other events were correlated with large meteors. At first this appeared to be typical meteor scatter, however the transients could not be characterized as man-made signals. The conclusion was then made that these were likely a newly discovered self-emission process, which were later termed meteor radio afterglows (MRAs).

Since the early days of radio astronomy meteors have been a speculative source of high frequency (HF; 3-30 MHz) and very high frequency (VHF; 30-300 MHz) radio emission. Gerald Hawkins conducted the first published experiment to search for meteor radio emission at 30, 218, and 475 MHz [3]. The experiment resulted in the detection of three pulses at 475 MHz and 20 at 30 MHz. All 23 events were coincident with optical meteors brighter than +4 magnitude. However it was pointed out that these events were likely due to the scatter of man-made emissions, a phenomena demonstrated in [4]. Indeed this is almost certainly the case given the low sensitivity of the experiment, but with no spectral information provided it is difficult to know exactly what was detected.

In the years to follow Hawkins' experiment, interest in meteor radio emission dwindled, which may have been in part due to the blossoming field of meteor radar. While HF and VHF radar became a popular method for studying meteors, radio astronomers moved to higher frequencies, mainly to gain higher angular resolution and to avoid complicated ionospheric effects. The lack of large HF/VHF radio telescopes delayed the eventual discovery of the natural HF/VHF meteor spectrum for many years.

Recent decades, however, have seen a renewed interest in radio astronomy in the HF and VHF bands and technological advancements in computing have ushered in a renaissance of many element HF/VHF radio telescopes. Notably the Long Wavelength Array (LWA) is a concept for a 52 station interferometer covering the state of New Mexico. Currently only two of these LWA stations have been built, but these alone are still highly sensitive and productive telescopes. The first station (LWA1), co-located with the Very Large Array in central New Mexico, was completed in late 2011 [5]. The second station, located 75 km northeast of LWA1 at Sevilleta National Wildlife Refuge (LWA-SV), began operation in early 2017 [6]. Each station consists of 256 dual-polarization dipole antennas spread across a 100m x 110m ellipse and are capable of all-sky imaging or beam forming. LWA1 operates anywhere in the 10-80 MHz frequency range, while LWA-SV can observe down to 3 MHz.

Figure 1. LWA-SV radio telescope: An photo taken from the middle of the array showing several of the dual-polarization dipoles.

The all-sky imaging capability of these telescopes make them ideal for studying the transient radio sky. In particular when LWA1 began operation in 2011 it was the first radio telescope to image the entire visible sky in real time. LWA1 continuously created all-sky images every 5 seconds, for nearly 16 hours a day,and quickly built a massive image archive. Without this capability, MRAs would have been very difficult to detect, given their rarity and low radio luminosity. The next sections describe the observations and characteristics of MRAs and the current hypothesis of the emission mechanism.

2 Observations and Characteristics of MRAs

MRAs currently have only been observed by LWA1 and LWA-SV, but other radio telescopes such as the Murchison Widefield Array (MWA)[7] and the Low Frequency Array (LOFAR)[8] have recently begun targeting them. The LWA stations have two main modes of operation. They can either act like an interferometer and image nearly the entire sky ($\sim$ 10,000 deg^2) or beam form on limited regions of the sky ($\sim$ 30 deg^2). The downside of all-sky imaging is that currently only 100 kHz of bandwidth can be used for continuous observations, whereas beam forming can provide up to $\sim$ 40 MHz bandwidth.

2.1 Temporal and Spatial Characteristics through All-Sky Imaging

The first observations were done using the all-sky imaging mode of the LWA1 [2]. The all-sky imager on LWA1 runs continuously in near-real time with a 5 second cadence. To search for transients we have implemented a simple image subtraction and thresholding algorithm. For the 5 s integrations we subtract off a running average of the previous 20 seconds. Similarly, we also search 15 s integrations (subtract the average of previous 45 seconds) and 60 seconds (subtract average of previous 60 seconds). Pixels above a 6 σ threshold are considered to be significant. These events are then filtered using their coordinates to exclude scintillating astronomical sources and galactic noise [9].

Before LWA-SV began regular observations in 2017, the only way to confirm a transient was a meteor was through the use of optical cameras. Fortunately both NASA Meteoroid Environment Office (MEO) and Sky Sentinel LLC operate fisheye video cameras in New Mexico, these cameras were crucial in both the discovery and followup observations. Optical observations are limited to clear nighttime observations, moreover [10] showed that the optical video cameras used by NASA/MEO and Sky Sentinel only detect roughly half of observable (i.e. clear nighttime) suspected MRAs.

MRAs often display similar characteristics, and are therefore relatively easy to identify. Looking at 37 optically confirmed and 87 suspected afterglows, [10] showed that $\sim$ 90% of optically confirmed afterglows displayed a light curve characterized by a fast rise followed by a slow (exponential looking) decay. Furthermore, with an angular resolution of $\sim 5°$, LWA1 resolved many events to be elongated in space, or to have multiple, spatially separated components. Using these characteristics, [10] estimated that at least 75% of the 87 suspected events were indeed MRAs. Many of the remaining events were too short and too dim to be characterized in the same fashion as the others. Based on these results, [10] estimated yearly rates for MRAs per solid angle. A telescope similar to LWA1 would expect to see about 60 events year^{-1} π sr^{-1}, at 38 MHz, although many of the events occur during high velocity meteor showers.

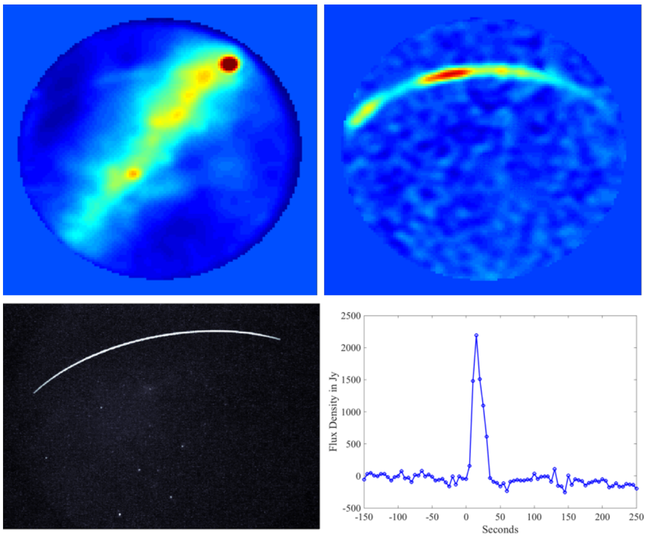

Figure 2. All-sky image of an Earth Grazing Meteor with Afterglow: The *top left* shows an all-sky image before subtraction, the image is dominated by the diffuse emission from the Milky Way galaxy, *top right* shows the image after the previous images have been subtracted removing the astrophysical sources and leaving only the MRA, *bottom left* shows an optical still of the same meteor, and *bottom right* shows the integrated flux density light curve of the radio afterglow. The event occurred on October 25, 2017 at 09:42 UT and lasted $\sim$ 30 s.

With the addition of LWA-SV we now simultaneously searching for events with both stations. Using anti coincidence and triangulation we can now identify and measure the position of MRAs occurring both night and day. Furthermore, with two stations we are able to remove false detections such as airplanes, satellites, or astrophysical sources with much higher fidelity.

2.2 Spectral Characteristics through Beam Forming

Since events are rare and for the most part unpredictable, all-sky imaging is crucial for identification and statistical analysis of MRAs. However, since only 100 kHz of bandwidth is available for all-sky imaging, beam forming has been our only tool for spectral analysis. Ideally, we would be able to trigger beam formed observations from the all-sky imager, however MRAs do not last long enough for triggered observations to be effective. We therefore determined that the best way to observe an afterglow spectra was to record beam formed data simultaneous with all-sky imaging. If an afterglow occurred in a beam we could identify it with the all-sky imager and then retrieve the spectra from the beam data. Due to computational limits LWA1 is only capable of producing three beams simultaneous with all-sky imaging, therefore, very few events are caught within a beam. Two such spectra were presented in [9], where the spectra were clearly broadband and not of man-made origin.

In [10], two more spectra were presented and all 4 were fit to a frequency dependent power law: $S \propto \nu^{\alpha}$, where S is the flux density, ν is frequency, and α is the spectral index. This study showed that all 4 spectra showed similar temporal evolution, where the spectrum evolved to get steeper (α getting more negative) over time. Initial values for α were between -2 and -5 and final values were between -8 and -12.

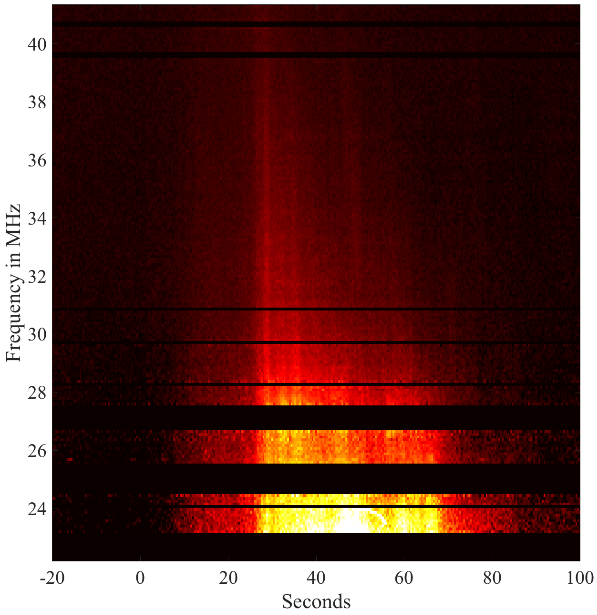

Figure 3. An example of a meteor radio after glow spectra: This event was reported in [10] and showed a broad spectrum following a frequency dependent power law getting brighter at low frequencies. Like other events, the power law dependence on frequency increased with time over the duration of the event. The black horizontal lines are due to masking of narrow band interference.

3 Plasma Wave Hypothesis and Future Work

MRAs are broadband and occur at a range of plasma frequencies expected in meteor trails. Therefore, [11] hypothesized that plasma waves may occur in some meteor trails, and due to large density gradients, these waves could leak into electromagnetic emission. This hypothesis is rather simple but does imply some observables that could be tested. For instance, plasma waves would be damped by the large number of collisions occurring within the trail. Indeed, [11] notes that the electron neutral collision frequency at 90 km is approximately 3×10^5 s^{-1} and gets exponentially higher at lower altitudes. While this collision frequency is exceptionally high, the observed plasma frequencies are on the order of 100 times larger, well above critical damping. Therefore, if a driving mechanism were to exist, plasma waves could grow within the trail.

However, any driving mechanism would need to compete with collisional damping. Since this damping is dependent on altitude, the occurrence of MRAs should also then depend on altitude. Using optical video cameras in conjunction with LWA1 observing [12] measured the altitudes of 44 different MRAs. This study showed that afterglows had a similar altitude distribution to optical fireballs above 90 km, but below 90 km there was a steep cutoff. Meteors or portions thereof below ~90 km appear to not produce radio emission. Such a cutoff agrees with the plasma wave hypothesis, but may also be caused by some factor other than collisional damping. An ongoing study is using LWA-SV and LWA1 to observe the altitudes of both day and nighttime radio afterglows.

If radio afterglows are indeed caused by plasma waves, then future observations could implement high resolution broadband imaging. If the LWA were upgraded to the full 52 stations (or at least 10 stations) such observations would be feasible. High angular and spectral resolution could be used to study the interaction between meteor trail plasma and the mesosphere. Currently we are conducting a proof-of-concept experiment using a single baseline (LWA-SV to LWA1).

Another challenge to the plasma wave hypothesis is related to the long duration of afterglows, which have been observed to last up to several minutes. In order to overcome collisional damping, the driving mechanism must provide sustained energy for a very long time. Such a mechanism may manifest itself through sustained optical emission. One possibility may be optical persistent trains, which are a well known but poorly understood phenomena where optical emission continues in the deposited plasma trail for many minutes after ablation [13]. An ongoing study is a using sensitive fish eye lens mounted on a sensitive CCD, colocated with LWA-SV to study persistent trains and see if there is any relation to MRAs.

4 Conclusions

Four years since their discovery, MRAs for the most part remain a scientific mystery. These events produce broadband HF/VHF radio emission for up to minutes after meteor ablation. They have been shown to occur with a strong altitude dependence, preferring altitudes above ~ 90 km. However, despite these advancements in describing the characteristics of afterglows, the underlying plasma physics has yet to be fully explained. Future experiments will focus on understanding the emission mechanism, and further explore the usefulness of meteors as probe of the mesosphere.

5 Acknowledgements

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