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SHORT-DURATION RADIO BURSTS WITH APPARENT EXTRAGALACTIC DISPERSION

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ABSTRACT

We present the results of the longest yet undertaken search for apparently extragalactic radio bursts at the Bleien Radio Observatory covering 21,000 hr (898 days). The data were searched for events of less than 50 ms FWHM duration showing a ν^{-2} drift in the spectrogram characteristic of the delay of radio waves in plasma. We have found five cases suggesting dispersion measures between 350 and 400 cm^{-3} pc while searching in the range of 75–2000 cm^{-3} pc. Four of the five events occurred between 10:27 and 11:24 a.m. local civil time. The only exception occurred at night with the full Moon in the beam. It was an event that poorly fits plasma dispersion, but had the characteristics of a solar Type III burst. However, we were not able to confirm that it was a lunar reflection. All events were observed with a log-periodic dipole within 6800 hr, but none with a more directional horn antenna observing the rest of the time. These properties suggest a terrestrial origin of the "peryton" type reported before. However, the cause of these events remains ambiguous.

Key words: intergalactic medium – radio continuum: general – surveys

Online-only material: color figures

1. INTRODUCTION

Short-duration broadband radio pulses have been predicted from several extragalactic processes, including giant pulses from pulsars (Cordes et al. 2004), prompt emission of gamma-ray bursts (Palmer 1993), and evaporating primordial black holes (Rees 1977; Osullivan et al. 1978). Such impulsive emission is delayed in a plasma relative to the speed of light. The delay is proportional to the traversed free electron column density, known as the dispersion measure (DM), and to ν^{-2} where ν is the observing frequency. A simultaneously emitted broadband pulse would thus show a characteristic drift in time and frequency, lower frequencies arriving later.

A number of previous searches for dispersed single radio pulses were negative. Particular galaxies were searched for several hours without detection of giant pulses (e.g., Osullivan et al. 1978; Cordes & McLaughlin 2003). Linscott & Erkes (1980) report pulses from M87 having a DM between 1000 and 6000 cm^{-3} pc, but Hankins et al. (1981) were not able to confirm them. Rubio-Herrera et al. (2013) published possible candidates from M31 having a DM of 54.7 cm^{-3} pc. Other searches were aimed at detecting radio pulses associated with gamma-ray bursts. No radio event was found by Benz & Paesold (1998), but Bannister et al. (2012) report two possible cases delayed from the gamma-ray peak by several minutes. Several general searches not aimed at particular objects were reported without detections. Amy et al. (1989) operated a transient event monitoring system for a total of 180 days at 843 MHz in parallel to interferometric observations at the Molonglo Observatory. Katz et al. (2003) did not observe any non-solar events within 18 months with the STARE system of three geographically separated instruments at 611 MHz. Siemion et al. (2012) did not detect any extragalactic pulses within 450 hr of a search with the Allen Telescope at 1430 MHz.

Recently four promising detections were reported from a general search with a multi-beam receiver of the Parkes telescope at 1358 MHz (Thornton et al. 2013). The events were detected in only 1 beam of 13, suggesting a non-terrestrial origin. The range of DMs was from 553 to 1103 cm^{-3} pc, the FWHM duration from $<$1.1 to 5.6 ms. The total observing time of the 13 beams amounted to 23 days each. In the various Parkes searches some 25 other pulses drifting as ν^{-2} were detected in all beams of the receiver, and thus seem to have come into the telescope through sidelobes (Burke-Spolaor et al. 2011). They are known as "perytons." These events show apparent DMs of 350–400 cm^{-3} pc, but some deviate from the strict dispersion delay. The reported fluxes are up to 272 kJy, and the FWHM durations are some 20 ms or more. An event reported earlier by Lorimer et al. (2007) was observed in several beams, lasted only 4.6 ms, but may be of a similar kind. Five more events just before a group of Burke-Spolaor events were reported by Kocz et al. (2012) and another four by Bagchi et al. (2012). Out of the 25 perytons reported so far, a group of 16 occurred within 30 minutes. Another two were found within one minute. Thus the number of independent events is nine, all observed at Parkes Observatory in New South Wales, Australia. Atmospheric conditions such as heavy rain or terrestrial X-ray and gamma-ray events were found not to be associated (Bagchi et al. 2012). If man-made, these signals traversing the globally protected frequency band at 1420 MHz (21 cm) would be illegal. Perytons are generally assumed to be terrestrial, but their origin is unknown and they can easily be confused with extragalactic pulses.

Here we report on long-term observations with small antennas having a large field of view but a short range in distance.

2. OBSERVATIONS AND DATA ANALYSIS

The program ASSERT (Argos Spectrometer Search for Extragalactic Radio Transients) is an observing project executed by the Institute for Astronomy at ETH Zurich. It is an independent system consisting of an antenna, receiver, spectrum analyzer, data taking unit, and off-line pulse detection algorithm. The observing time was 24 hr per day, with rarely more than a few hours of down time per months for calibration and to put a new hard disk in place.

2.1. Instrumentation

The observations were made at the Bleien Observatory of ETH Zurich some 50 km west of Zurich, Switzerland (E08° 06′41″, N47° 20′23″). First, a commercial log-periodic dipole (R&S HL-040, gain $G \approx 4$ at 1420 MHz) pointed to the local zenith was used as the receiving antenna. At 1500 MHz it has an FWHM beam width of 70° in east–west and 110° in north–south. Calibration with the quiet Sun yields a conversion factor of 270 kJy K^{-1}. The log-periodic antenna was in operation starting on 2009 June 3 until 2010 March 18. It was replaced after this date by a more directive horn antenna having an FWHM beam width of 10°, operating until 2011 November 21. The horn was mounted to the south, scanning the sky at a declination of $-14° 40'$.

The receiver is a 16,384 channel Fourier-transform spectrometer (Benz et al. 2005) with 8 bit sampling and a bandwidth of 1000 MHz. The effective bandwidth was reduced by filters to avoid terrestrial interference. The useful range was from 1150 to 1740 MHz. The intrinsic frequency resolution is 64 kHz, integrated on-line to 1.02 MHz. One spectrum is obtained every 10 ms.

For both antennas, the system temperature of ASSERT is between 90 and 240 K depending on frequency; the average being 180 K. It was calibrated with the quiet Sun and several times per year using an external noise source.

The Bleien Observatory also includes various radio telescopes that continuously observes the radio emission of the Sun in daytime from 20 MHz to 850 MHz and 1100 to 1700 MHz. These solar dedicated sensitive observations pointed to the Sun make it easy to identify solar radio bursts detected by ASSERT. The solar receiving systems are also sensitive to pulses caused by terrestrial lightning in all directions and within hundreds of kilometers. Thus atmospheric discharges can be identified over a large frequency range. Their emission is predominately <200 MHz. The observatory is remotely controlled and has no permanent personnel on site. The activity of persons visiting for service and maintenance is well documented in a logbook. A weather monitoring station records wind, rain, temperature, and humidity.

2.2. Data Analysis

Radio bursts of interest were searched using the following methodology. To ensure that no burst would be cut in half by scanning each file individually, data chunks (consisting of a central file, with the last half of the preceding file prepended, and the first half of the following file appended) were employed (in effect, all the data was scanned twice). Each data chunk was "cleaned" of interference channels by using standard software developed over the years at ETH Zurich to analyze solar radio data (basically, channels that average out to be much higher than the average of their neighbors are omitted). In an effort to remove patches of bad pixels (due to various types of spurious sources or man-made interferences), the data was then "despiked" in the following manner. Each pixel that is more than 25 K (an ad hoc value, corresponding to about 5 MJy for the log-periodic antenna, and about 75 kJy for the horn antenna) above the channel's average is checked against its 24 nearest neighbors (a 5×5 window). If no pixel within that 5×5 window is within 10 K (another ad hoc value) of the central pixel, then it is assumed we have a non-continuous source, and it is hence discarded. A 1 s gliding average for each channel was then removed to obtain a background-subtracted spectrogram.

The data were then rebinned in 5 ms bins, and were dedispersed, for each DM between 75 and 2000 cm^{-3} pc, in 25 cm^{-3} pc increments, assuming a ν^{-2} dispersion law. In a dedispersed spectrogram, each channel is time-shifted such that a burst with the appropriate DM would appear as a vertical line in the spectrogram. The de-dispersed data are then integrated in frequency in order to obtain a single time profile.

The DM value for which the time profile's peak is highest is assumed the burst's DM. Such time profiles are shown in Figure 1, as well as their associated spectrograms. The signal-to-noise ratio (S/N) was computed by dividing the peak of the time profile by the standard deviation of the time profile. Likewise, a Gaussian was fitted to each peak in the time profiles, yielding an FWHM duration as shown in Table 1. All the burst candidates were ordered by their S/N figure in a master list, from highest to lowest. Candidates with S/N less than six were dropped. This master list comprised of about 22,325 candidates. We decided to further restrict ourselves to bursts with less than 50 ms FWHM duration, and with DM equal or greater than 75 cm^{-3} pc, which were examined manually to eliminate the many remaining false positives caused by obviously man-made interference. In the end, only five candidates were found. They are discussed in the next section.

3. RESULTS

The five most prominent burst candidates are displayed in Figure 1 and characterized in Table 1. They all have positive DMs. Events with negative DMs can result from superpositions of obvious interference. None of them were continuous through the band as the events shown in Figure 1.

As is obvious from Figure 1, bursts vary strongly in intensity at different frequencies. The peak flux value can easily be an order of magnitude higher than the "average flux" values given in Table 1. We note that the five DMs are within a small range between 350 and 400 cm^{-3} pc. They last between 17 and 25 ms; thus, they significantly exceed the values reported by Thornton et al. (2013), and resemble more the "peryton" class of events reported by Burke-Spolaor et al. (2011).

The last event (Figure 1, bottom) is different in several ways. It appears to be linear in the spectrogram representation, contrary to the first four events that are clearly bent. The last event occurred at night time, but the other four in a very narrow time interval, which is even narrower in civil time adjusted for daylight saving time. In the latter frame of local civil time, the four events occurred within 1 hr, between 10:27 and 11:24 a.m.

The following auxiliary data were searched for possible origins.

1. The logbook of the Observatory has no entries for the five days. Thus no personnel were on site and no laboratory equipment in operation.
2. The weather data reporting on rain, humidity, wind, and temperature do not show any unusual particularities at the time of the observed events.
3. A possible atmospheric discharge is visible in the solar observations 4.5 minutes before the 2009 July 8 event from 20 to 80 MHz. In the spectrogram of the 2009 November 6 event, a broadband short but not drifting event is present at 17.69 s after 09:54:17 UT (Figure 1, fourth from the top). However, there was no thunderstorm listed in Switzerland for that day (www.meteo24.ch). We note, however, that the propagation range of microwave lightning signals may

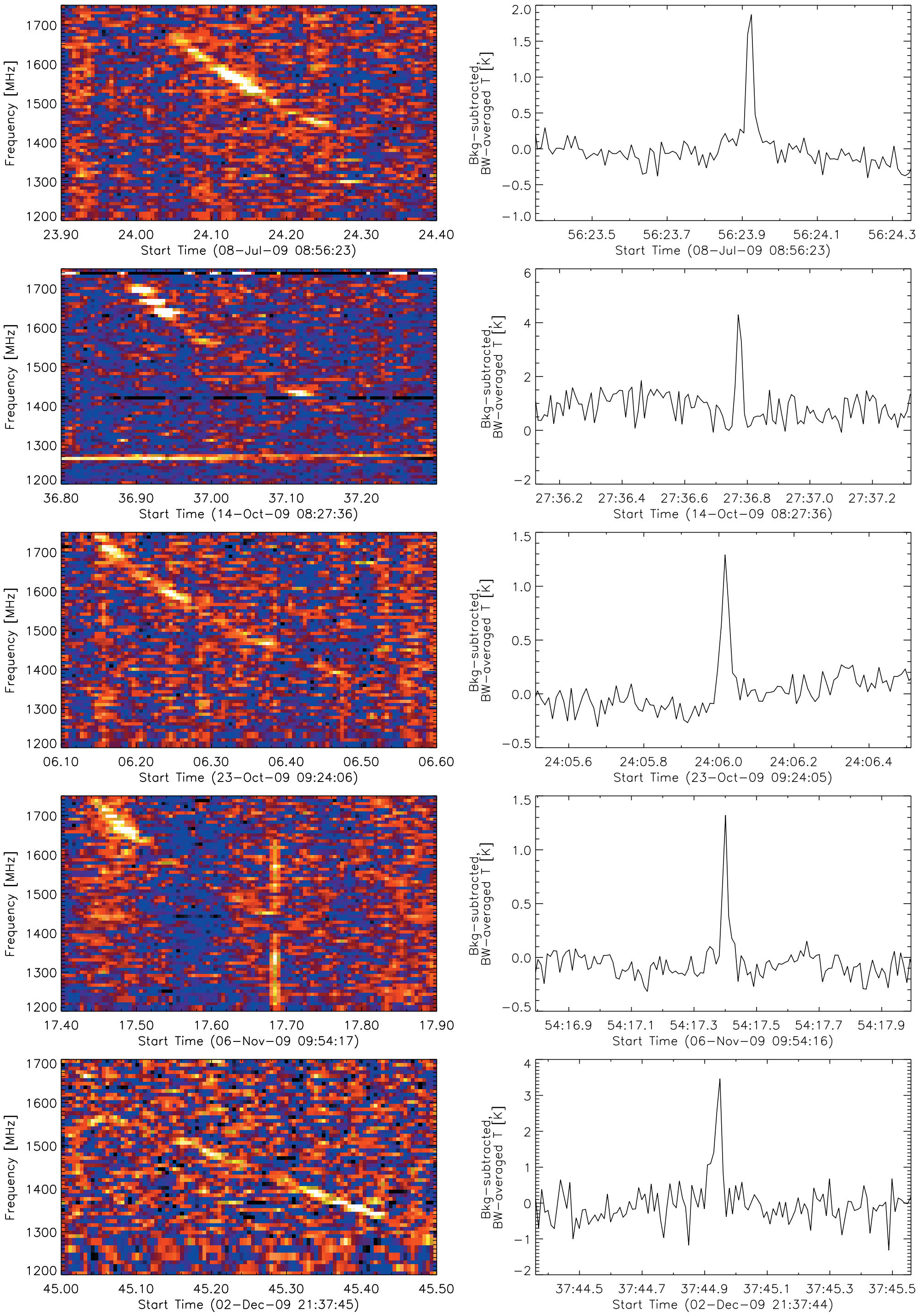

Figure 1. Original spectrograms observed with the ASSERT system and frequency-cumulated de-dispersed lightcurves.

(A color version of this figure is available in the online journal.)

exceed 1000 km (Petersen & Beasley 2014 and references therein).

4. There was no solar event observed by the time of the four events that occurred in day time.
5. The 2009 December 2 event occurred at night within 14 hr of the full Moon. The position of the Moon was within the FWHM beam.

At this point, we further stress that our search algorithm was optimized to find bursts with a ν^{-2} dispersion law. As shown with the last burst of Table 1, this slightly diminishes the chances of detecting bursts with linear drift rates.

Finally, we note that the initial search methodology was optimized to find very smooth and weak dispersed signals (the "Lorrimer burst" had a flux of 30 Jy only). After having found the 2009 events (all very powerful, and exclusively with the log-periodic antenna), we redid a scan of the 2011 data (horn antenna), with a simpler and more encompassing de-spiking procedure: we simply removed pixels more than 650 K (about 2000 kJy for the horn antenna) above the channel average, and

Table 1
Detected Events in This Search, Signal-to-noise Ratio, Dispersion Measure DM, FWHM Duration Δt, and Band-averaged Flux Density

Date (yyyy/mm/dd)	Time (UT)	Civil Time [MEST/MET]	S/N	DM (cm^{-3} pc)	Δt (ms)	Averaged flux (kJy)	Comment
2009 Jul 8	08:56:23	10:56:23	10.2	400	21.6	360	
2009 Oct 14	08:27:36	10:27:36	16.4	350	20.2	840	
2009 Oct 23	09:24:06	11:24:06	10.8	350	23.4	250	
2009 Nov 6	09:54:17	10:54:17	10.1	350	17.3	250	
2009 Dec 2	21:37:45	22:37:45	7.3	375	24.9	690	assuming $\Delta t \propto \nu^{-2}$
			8.6	−610*	24.2	1090	assuming $\Delta t \propto -\ln \nu$

Note. A linear drift rate (leading to a log dispersion) has also been used on the last burst, and its DM entry (marked by an "*") is actually an average drift rate in MHz s^{-1}.

replaced them with the channel average: no new candidates were found.

4. DISCUSSION

Thornton et al. (2013) report a rate of $1.0^{+0.6}_{-0.5} \times 10^4$ of their type of bursts per day on the full sky. As the limiting fluence of the very directive Parkes observations, F_P, we take their weakest event, 0.6 Jy ms. A small antenna is less sensitive to a point source, but has a larger field of view. The sensitivity limit of ASSERT was tested by adding an artificial event to real background data. An event of 2.5 K antenna temperature lasting 10 ms is detected with an S/N of 10 for both antennas. The detection limit of ASSERT is thus 25 K ms, or a fluence of 5660 kJy ms for the log-periodic antenna, and 92 kJy ms for the horn antenna. Thus the ASSERT range of detection, d_A, is 3.3×10^{-4} times smaller than the Parkes antenna for the log-periodic antenna, and 2.6×10^{-3} times smaller for the horn antenna. On the other hand, ASSERT views a larger angle of the sky.

Assuming a constant rate of events per volume having the same luminosity, the number of observable events, N, is given by

$$N = V\ R\,\Delta t, \tag{1}$$

where V is the volume observed by the antenna, R is the rate of events per volume and time, and Δt the observing time. V is given by the volume of the spherical sector.

$$V = \frac{2\pi d^3 \left(1 - \cos\left[\frac{\theta}{2}\right]\right)}{3}, \tag{2}$$

where θ is the FWHM beam angle of the antenna. The reported rate of Thornton et al. (2013) amounts to the events in a sphere with a radius given by the Parks range of detection, d_P. Thus

$$N_A = \left(\frac{d_A}{d_P}\right)^3 V_P R \frac{1}{2}\left(1 - \cos\left(\frac{\theta_A}{2}\right)\right)\Delta t_A. \tag{3}$$

Using the parameters given before, the numbers of expected events during the ASSERT observing times are

$$N = 4.9 \times 10^{-5} \quad \log - \text{periodic antenna}, \tag{4}$$

$$N = 5.1 \times 10^{-2} \quad \text{horn antenna}. \tag{5}$$

On this basis, we were unlikely to find Thornton-class events, even if looking for them at the very low DM expected for short ranges, a difficult endeavor because of natural and man-made radio-frequency interface.

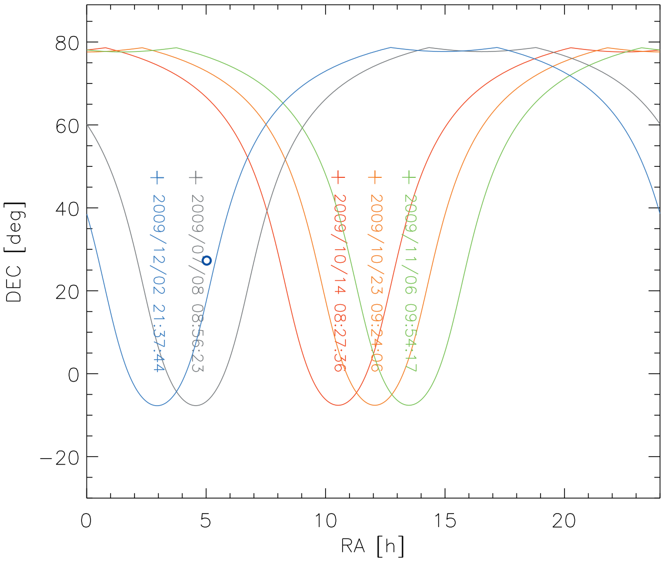

Figure 2. Pointing (plus signs) and halfpower beam (curves) of the antenna projected to the sky at the times of the five events reported in Table 1. The position of the Moon on 2009 December 2 at 21:38 UT is indicated with a blue circle.

(A color version of this figure is available in the online journal.)

Figure 2 displays the antenna pointing and half-power beam in equatorial coordinates at the time of the five events listed in Table 1. The pointing at the time of the events is widely distributed on the sky. Assuming that the radiation originated from the same source, it would have to be within about 10° of the north celestial pole.

4.1. *Was the 2009 December 2 Event a Solar Burst Reflected by the Full Moon?*

Electron beams propagating in the solar corona emit radio waves at the local plasma frequency or its harmonic (review, e.g., in Benz 2002). The drift rate of the observing frequency, $\dot{\nu}$, in a barometric isothermal atmosphere depends linearly on frequency

$$\dot{\nu} = -\frac{\nu v_s \cos\theta}{2H_n(1 - \beta\cos\Phi)} \equiv -\frac{\nu}{T}, \tag{6}$$

where v_s is the beam velocity in upward direction, $\beta = v_s/c$, H_n is the density scale height, Φ and θ are the angle between the beam direction and the vertical, resp. the radiation path to the observer. $T > 0$ for upward beams in the corona. The delay

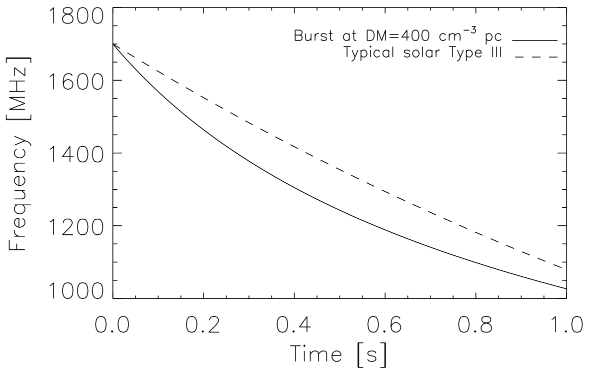

Figure 3. Expected peak emission times for a plasma-dispersed burst and for a solar Type III burst.

thus follows the relation

$$\delta t = -\frac{T}{\nu}\delta\nu. \tag{7}$$

Leading to a $\nu(t) = \nu_{\mathrm{ref}} e^{-(t-t_{\mathrm{ref}})/T}$ drift relation. The drift of a solar electron beam is therefore less bent than the drift due to plasma dispersion,

$$\delta t = -\frac{e^2 \mathrm{DM}}{\pi c m_e \nu^3}\delta\nu \tag{8}$$

(Benz 2002) which leads to the drift relation:

$$\nu(t) = \frac{1}{\sqrt{\frac{1}{\nu_{\mathrm{ref}}^2} + (t - t_{\mathrm{ref}})/C}}, \tag{9}$$

with $C = (e^2/2\pi c m_e)\mathrm{DM}$. The former is much more linear in appearance than the latter for the typical ≈0.5 s durations we are dealing with (Figure 3).

The event on 2009 December 2 drifts with a rate of -610 ± 20 MHz s^{-1}. This is in the range of solar Type III bursts at decimeter wavelengths (Benz et al. 1983), where the minus sign indicates a beam propagation in an upward direction through the corona. Scattering by the Moon reduces the radio flux by a factor of 9.3×10^{-5}, assuming a lunar radar cross section of 0.065 (Evans & Hagfors 1966). The observed average flux of the event (Table 1) would require a flux of 7.4×10^9 Jy before isotropic reflection.

We have searched the RSTN data[3] for solar radio emission. However, we were not able to confirm a simultaneous solar burst exceeding 10^4 Jy at 1415 MHz. We note, however, that on the same day an isolated solar Type III B was observed at the Bleien Radio Observatory at 08:47.6 UT (Solar and Geophysical Data, NOAA), but not recorded by RSTN. No flare was reported from *GOES* X-ray data at the time of both events. For decimetric Type III bursts this is not unusual; on average, 61% are associated with soft X-rays, but less for isolated bursts (Aschwanden et al. 1985). Thus there is little evidence for a solar event reflected by the Moon. However, any exciter moving at constant speed upward in an exponential atmosphere (static and isothermal) would cause this signature of a solar-like event. Such events were proposed by Kulkarni et al. (2014) and Tuntsov (2014).

5. CONCLUSIONS

Five events of plasma-dispersion-like drifts in frequency have been observed in an observation of several years. These events have the following properties.

1. The detection rate is much higher than the one-beam events reported by Thornton et al. (2013).
2. The duration is of the order of 20 ms.
3. The DM is in the range of 350–400 cm^{-3} pc.
4. The bursts vary strongly in intensity at different frequencies.
5. All events were observed with the low-directional log-periodic antenna and they are fairly evenly distributed on the time scale of days in the first six months of its operation. Then no events were detected for three months, after which it was replaced with the horn antenna.
6. Four out of five bursts occurred between 10:27 a.m. and 11:24 a.m. local civil time. Thus the events are non-random in local daytime.
7. One out of five events deviates from the strict dispersion delay. No events were detected in the twenty months of observations with the more directive horn antenna.
8. No solar events were observed at the time of the events.
9. No laboratory equipment was operated at the time of the events.
10. No lightning or other atmospheric phenomena were recorded on site at the time of the events.

The burst characteristics (duration, DM, variable intensity, and non-random distribution in daytime) are more consistent with the many-beam events observed with the Parks Telescope (Burke-Spolaor et al. 2011) than the single-beam events reported by Thornton et al. (2013). Burke-Spolaor et al. (2011) created the name “perytons” to describe their deceiving resemblance with extragalactic events, but showing presumably terrestrial origin. Four out of our five events have a clear ν^{-2} frequency drift, making them strikingly similar to the previously reported perytons. The frequency drift of the fifth event fits better the signature of an exciter moving upward in an exponential atmosphere with constant velocity.

Our peryton-like events were independent and well separated in time. Their rate is about 1 per 70 days observed with the log-periodic antenna. These events are the first ones of this kind observed outside of the Parks Observatory region. Their origin remains unexplained.

Future observations of short-duration radio bursts may explore lower frequencies where the detection of low DM events is easier or use a higher gain antenna for more sensitivity.

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