Atmospheric Interpretation of Anomalous Terrestrial Emission Serendipitously Discovered in Radioastronomy Data at 1 Gigahertz

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Abstract

A publication in the Astrophysical Journal [1] reported the discovery of swept-frequency, terrestrial emission in a search for astrophysical pulses. The emission's origin has yet to be determined; its attributes are atypical of known sources of terrestrial signals. We review the observed properties of the emission and present a simple model for a physical mechanism that could occur in the atmosphere to produce it. If this mechanism is the cause of the emission, its origin may lie in secondary effects of lightning production in the upper atmosphere.

1 Introduction

Searches for isolated astronomical radio pulses have grown in popularity following a number of recent discoveries [e.g. 2-3]. The surfeit of Earth-origin (man-made and natural) pulses requires these searches to use techniques that discriminate target signals from terrestrial pulses. A basic feature of astronomical pulses is their frequency-dependent delay, which follows $\delta t \propto f^{-2}$. This is an additive dispersion effect resulting from propagation through interstellar plasma that is negligible in locally-generated emission (see Fig. 1).

Recently, sixteen *terrestrial* pulses with frequency-swept characteristics that mimic an astronomical dispersion delay were reported [1]. They were found in data taken at sparse intervals over the years 1998–2003, using the multibeam receiver on Parkes Radio Telescope in Australia and a specialized back-end hardware that allows 96 spectral bands to be sampled across a 288 MHz bandwidth centered at $f = 1.375$ GHz. The pulses were distinct among the other discoveries from the search: they were detected through a sidelobe of the telescope, exhibited multi-path interference, and at times deviated from a model dispersion sweep (Fig. 1; see also Fig. 6.5 of [4]). They appeared more frequently in June/July, and mid- to late-morning. When measured over a narrow band, all pulses were 30–50 ms duration, and clustered bimodally in sweep rate with a primary peak at 0.8 GHz/s and a small peak at 1.4 GHz/s. Lacking a physical descriptor for their origin, the pulses were labelled "Perytons". We hereafter refer to them thus.

Drastic frequency-dependent delays at 1 GHz band are highly anomalous of terrestrial emission, which is typically either narrow-band, or broadband but unswept. Ref. [1] determined that Perytons are not likely generated by manmade, Earthbound transmitters. Peryton detections in data from 2010 strengthen their arguments [5]. We explore the possibility that Perytons are caused by a natural atmospheric process, through which radio waves are generated in a plasma of changing density. We then note the circumstantial relationship between the Perytons' limits on this model and upper-atmospheric transient luminous event phenomena.

2 The natural production of highly-swept emission

Producing the properties of the observed emission in the absence of interstellar dispersion effects requires a finite-bandwidth ($\Delta f \simeq 25$ MHz) signal to progressively change its center frequency. This can occur naturally, for instance, by the generation of cyclotron emission in a magnetic field of time-varying strength, or the conversion of Langmuir waves into electromagnetic emission in a plasma of varying density. It is via the second of these mechanisms that we explore the production of Perytons here.

In this mechanism, a propagating flare induces plasma oscillations that undergo a mode-conversion process, which partially converts the Langmuir waves into electromagnetic emission at the plasma frequency (or its second harmonic). As the flare propagates, the resulting emission rises or drops in frequency, corresponding to plasma density changes. An example of this process is the swept emission observed in type III solar bursts [6]; in that case, a flare propagates outward through the solar wind, whose density falls with

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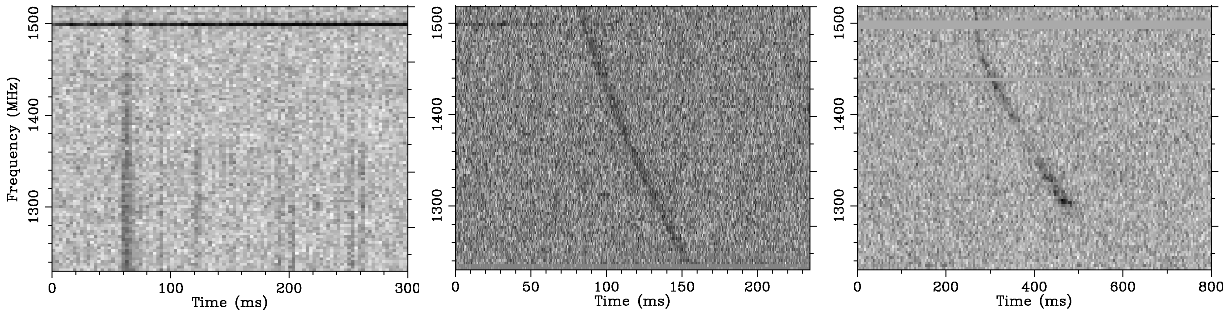

Figure 1: Spectrograms of three distinct-origin signals. Power is in greyscale (black, higher power) as a function of f and time. Left, typical local signals (broadband and unswept, and a narrowband signal). Middle, a dispersed pulse from pulsar J1129-53. Right, a Peryton. This Peryton exhibits a "kink" in its sweep at $\sim$1470 MHz, definitively indicating that the sweep is not plasma dispersion. The Peryton's frequency modulation is attributed to multi-path scattering. Narrow-band interference is blanked here.

distance from the Sun. The Langmuir wave mode-conversion process results in radio emission observed as a frequency-swept burst as oscillations are incited in regions of lower density. We note that the Perytons are of too short duration, too bright, and occur at too high a frequency to be type III solar bursts. Nevertheless, the Langmuir wave-conversion model has applicable properties to the observed characteristics of the Perytons.

2.1 Basic model parameters

A plasma emitting at a radio frequency f has a free electron density, n_e, that obeys $f = \sqrt{n_e e^2/(m_e \epsilon_0)}/2\pi$. We consider a plasma with a continuous density distribution $n_e(h)$ along axis h. If $n_e(h)$ is known, the expected frequency-dependent delay exhibited by an incident flare undergoing Langmuir-wave mode conversion can be calculated considering that the delay between two points h_1 and h_2 is simply $\Delta t = (h_2 - h_1)/v$, where v is the incident flare velocity. The basic spectral and spectral-sweep properties resulting from such emission thus clearly depend on the density and density gradient of the ambient plasma, the velocity of an incident flare, and the propagation direction of the flare along the density gradient. Throughout this analysis we consider only a one-dimensional gradient and propagation vector.

2.2 Investigation of atmospheric plasma origins

The Perytons were detectable across the entirety of the observing band ($f_1 = 1.5165\,\mathrm{GHz}$ to $f_2 = 1.2285\,\mathrm{GHz}$), requiring plasma electron densities from $n_{e1} \simeq 2.9 \times 10^{16}/\mathrm{m}^3$, to $n_{e2} \simeq 1.9 \times 10^{16}/\mathrm{m}^3$, or one fourth of these values if the second emission harmonic was detected. Emission produced in the atmosphere requires a plasma to be ionized to this level, and to have a continuous change in n_e over a factor of $\sim$1.5. Even at maxima in the ambient n_e of the ionosphere, the plasma densities are too low to produce emission at 1 GHz [7]. However, such electron densities have been observed to be transiently reached by ionized channels that accompany electrical storm phenomena, likely ranging $>10^{10}\,\mathrm{m}^{-3}$ for upper-atmospheric "red sprites" [8], up to $10^{23}\,\mathrm{m}^{-3}$ for cloud-to-ground lightning [7]. A super-ionisation event of this magnitude would be required for emission via this model in the band at which the Perytons were observed.

We therefore investigate the suitability of an atmospheric Langmuir wave emission model by considering the most simple case of flare propagation along a vertical, lightning-induced plasma channel ionized at a fraction q of the atmospheric density. We approximate the electron density at altitude h to be equal to a fractional level of the atmospheric atomic number density, $n_{\mathrm{atm}}(h) \simeq \rho(h) N_A / M(h)$, where N_A is Avogadro's constant, and $M(h)$ and $\rho(h)$ are the mean atomic weight and density of the atmosphere at altitude h. We then can estimate $n_e(h)$ in the channel by fitting the altitude-dependent atmospheric densities reported in the "US Standard Atmosphere 1976" (USSA) [9], defining an upwards normal vector:

$$n_e(h) \simeq q \cdot n_{\mathrm{atm}}(h) = \begin{cases} [\rho(0) N_A / M(0)] \cdot \exp(h/7\,\mathrm{km}) & \text{for } h \leq 120\,\mathrm{km} \\ 4.7 \times 10^{29}\,\mathrm{m}^3\,(h/\mathrm{km})^{-6} & \text{for } h > 120\,\mathrm{km} \end{cases} . \quad (1)$$

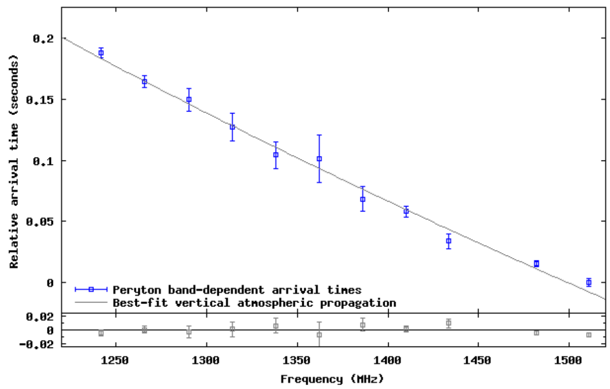

Figure 2: A Peryton's f-dependent arrival and the best-fit emission model. The upper panel shows the arrival time (blue) in 24-MHz-averaged bands relative to the 1512 MHz arrival. The Eq. 2 ($h < 120\,\mathrm{km}$, $q_1 = q_2 = 1.0$) fit is plotted in gray. The lower panel shows the residuals after model subtraction.

The piecewise function reflects the change in atomic makeup near the base of the ionosphere. Eq. 1 allows us to determine the f-dependent delay for a vertical ionisation channel when incited by a flare of velocity v:

$$\delta t = \begin{cases} 14 \cdot \ln[(q_2 f_1)/(q_1 f_2)]/v & \text{for } h \leq 120\,\mathrm{km} \\ (g/b)^{1/6}(\sqrt{q_2}/f_2)^{1/3} - (\sqrt{q_1}/f_1)^{-1/3})/v & \text{for } h > 120\,\mathrm{km} \end{cases}, \quad (2)$$

where $g = 4.7 \times 10^{29}\,\mathrm{m}^3$, $b = 4 m_e \epsilon_0 \pi^2/e^2$, and q_1, q_2 correspond to the ionization fraction at h_1 and h_2, respectively. Setting $q_1 = q_2 = 1.0$ (i. e. complete atmospheric ionization), a fit of this equation to the frequency-dependent arrival times of one Peryton is shown in Fig. 2. This fit demonstrates that a flare travelling *upward* through such a channel can produce a frequency-dependent sweep in agreement with the data. Deviations from a smooth frequency/altitude-dependence may be introduced by local density variations. The observed sweep rates for the Perytons imply flare velocities ranging 7 to $15\,\mathrm{km\,s^{-1}}$, again assuming vertical orientations and $q = 1.0$. The clustering of the Perytons' sweep rates indicates that there would be a characteristic (possibly bimodal) velocity distribution. However, the velocity value estimates will change if one or both of the following applies to our simple model: a) q is altitude-dependent, leading to steeper n_e gradients, or b) The channels of ionization (and thus progression of emission) are non-vertical.

The electron density cannot exceed the electrons available in the ambient atmosphere, thus the height of the emission is limited to the height below which the atmospheric atomic number density could produce plasma oscillations at 1 GHz. At f_1, if the detections were a second emission harmonic, that limit is $< 200\,\mathrm{km}$, and for a detection of the first emission harmonic, the limit is more stringent ($< 163\,\mathrm{km}$).

If this mechanism is indeed the cause of the Perytons, several implied properties point to a relationship with upper-atmospheric storm phenomena such as the aforementioned red sprites or gigantic jets [10, 11]. This includes the upward propagation to produce the high-to-low frequency sweep and the $h < 200\,\mathrm{km}$ altitude limit, in addition to the high plasma density and $>$350 ms ion persistence time necessary to produce the full signal, which implies that the emission would be required to occur at high altitude.

2.3 Weather-related Effects: Ducting, Annual Cycles, and Storm Activity

June/July is not the peak of Australian storm season, however does coincide with mid-winter. The recorded weather statistics indicate that despite a drought, moderate rainfall occurred on 3/4 detection days for which data was available. We suggest that such weather conditions and the atmospheric state on mid-winter mornings provide a high likelihood for elevated tropospheric ducts to form [12, 13], allowing a larger detection range than is usually detectable, and inducing the observed annual and diurnal typical detection occurrence. Elevated mid-winter-morning detections of transmitters known to be beyond the Parkes horizon provide strong support for this hypothesis [14]. Australian lightning activity was not statistically heightened on days of the detections [15], however we do find cloud-to-ground lightning strikes indicating electrically active oceanic storms occurring during each event, at distances $< 2000\,\mathrm{km}$ from the telescope. These coastal storms represent possible origins for lightning-related emission in the presence of a tropospheric duct.

3 Conclusions and future directions

We outlined a simple atmospheric Langmuir mode conversion model that can reproduce the basic characteristics of Perytons, with circumstantial evidence relating the model to upper-atmospheric electrical events. We considered only the simplest geometric configurations and models of lightning-related ionization, and a more realistic model of transient atmospheric plasmas has yet to be explored. We note that if the suggested mechanism is giving rise to Perytons, it would allow direct measurements of the altitude-dependent plasma electron density in lightning-induced ionization channels. A definitive Peryton origin is currently impeded by their sparse event rate and the specialized hardware needed to identify. An ongoing survey at Parkes Telescope has the capability of detecting Perytons, and has uncovered two so far [5]; however, single-dish telescopes cannot determine the arrival direction of local signals. Localization requires several broadly-spaced receivers, equipped with backends capable of detecting the broadband, swept-frequency signature of Perytons. However, we know of no apparatus currently operating that has such capabilities.

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