Day 2:

Explosive or Irreversible Changes

https://doi.org/10.1017/S1743921312000208 Published online by Cambridge University Press

New Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 285, 2011
R.E.M. Griffin, R.J. Hanisch & R. Seaman, eds.

doi:10.1017/S1743921312000208

The Dynamic Radio Sky

James M. Cordes

Astronomy Department, Cornell University, Ithaca, NY 14853, USA
email: cordes@astro.cornell.edu

Invited Talk

Abstract. The radio band is known to be rich in variable and transient sources, but exploration of it has only begun only in the last few years. Relevant time scales are as small as a fraction of a nanosecond (giant pulses from the Crab pulsar). Short transients (less than one second, say) have signal structure in the time-frequency plane at the very least because of interstellar plasma propagation effects (dispersion and scattering), and in some cases due to emission structure. Optimal detection requires handling a range of signal types in the time-frequency plane. Short bursts by necessity have very large effective radiation brightness temperatures associated with coherent emission processes. This paper surveys relevant source classes and summarizes propagation effects that must be considered to optimize detection in large-scale surveys. Scattering horizons for the interstellar and intergalactic media are defined, and the role of the radio band in panchromatic and multimessenger studies is discussed.

1. Introduction

Transients across the electromagnetic spectrum as well as in neutrinos, cosmic rays and gravitational waves are of special interest because they carry information both about sources, particularly their energetics and environments, and also about intervening media. Comprehensive all-sky surveys of transients have been made for decades in the X-ray and gamma-ray bands. Detectors in those bands and in other tracers (cosmic rays, neutrinos and gravitational waves) inherently have wide fields of view (FoV). Telescopes that involve mirrors have relatively small FoVs; that is especially true at radio frequencies, where large antennæ have traditionally been used to achieve requisite sensitivities (i.e. $A\Omega = \lambda^2$). For that reason, much of the phase space for radio transients is unexplored, especially those that have low rates. It is possible that very bright but rare radio transients occur and can be detected with even small collecting areas.

The current situation is being rectified at radio wavelengths under the paradigm where a large number of small antennæ ("large-N/small-D") are used to supply adequate collecting area. At centimetre wavelengths a large number of small dish antennæ provides both large total area (NA) and large FoV ($\Omega \sim N_{\rm pix}\lambda^2/A$). Focal-plane arrays are increasingly being used to provide multiple-pixel ($N_{\rm pix}$) systems. Feed clusters are used at higher frequencies and phased-array feeds are in an R&D phase for frequencies ~ 0.5 to 1.5 GHz. At metre wavelengths a similar approach uses phased-arrays comprised of dipole antennæ instead of dish concentrators, yielding radian-like FoV (e.g. LOFAR, Long-wavelength Array [LWA]).

Synoptic surveys in the radio band are essential for several reasons. First, the Venn diagram of transients includes some overlap of source classes (e.g. gamma-ray burst [GRB] afterglows) between radio, optical-infrared (OIR), and X-rays along with significant *non*-overlap (e.g. coherent radio bursts, optical novæ). Comprehensive surveys can therefore use radio and OIR transient detections in source classification. On the other hand, radio and gamma-ray transients show a great deal of commonality in blazars and pulsars.

While prompt radio bursts from GRBs have yet to be seen, in terms of energy it is very plausible for such bursts to exist and yet to have been missed so far because of insufficient temporal and sky coverage. In the rest of this paper, I discuss source types, propagation effects and some of the observing programmes that are likely to take place this decade.

2. Radio Transients

Nature can be profligate in producing radio photons and thus make sources detectable. It does so in many cases via coherent radiation processes that give N^2 rather than N scaling from a collection of N particles. In most sources radio emission is not the dominant energy channel for dumping free energy, but it is an extremely significant information channel. Examples include pulsars and radio pulses from ultra high-energy cosmic rays.

2.1. *Fast and Slow Transients*

It is useful to classify the wide range of time-scales in terms of how they are best sampled empirically. For radio telescopes with conventional fields of view, such as those provided by paraboloids with single-pixel feeds, slow transients are those that can be sampled in a raster scan survey because they stay “on” for at least as long as it takes to scan the relevant sky region (e.g. the Galactic plane, the Galactic centre or the entire sky). Depending on survey speed, transients of days or more may be considered “slow”.

Fast transients, conversely, are those that would be missed in the time it takes to scan the sky, leading to incompleteness of the survey. Sub-second transients are linked to coherent radiation and, by making a simple light travel-time argument, to sources in extreme matter states. They are also affected by plasma propagation effects such as dispersion and multipath scattering, which can distort pulses and inhibit detection. By the same token, such transients are excellent probes of the intervening interplanetary, interstellar and intergalactic media.

2.2. *Examples*

All known, convincing, fast radio transients appear to be Galactic in origin because the column density of electrons toward them can be accounted for by the Milky Way. No firm statements about slow transients can be made on that basis because propagation effects do not affect the transient burst shape, although interstellar scintillation can modify the apparent flux density (see below). Examples of fast transients include giant pulses from the Crab pulsar, modulations of pulsar signals, rotating radio transients (RRATs; McLaughlin *et al.* 2006) and some solar bursts. Transients with long time-scales include intermittent pulsars that turn on and off on time-scales of weeks to months, magnetars that are pulsed at rotation rates ~ 5 to 10 s but are on or off over time-scales of years (Camilo *et al.* 2006), flare stars (Osten & Bastian 2008), brown dwarfs, GRB afterglows (with and without gamma-ray emission), and tidal disruption events. There are, of course, long-duration transients seen in imaging surveys that are not yet identified definitively (Hyman *et al.* 2006, Bower *et al.* 2007, Frail *et al.* 2011, Ofek *et al.* 2011).

2.3. *Phase Space*

In the two-dimensional space of peak flux density ($S_{\rm pk}$) and time-scale, known radio transients range from 100 μJy to > 1 MJy (more than 10 decades) and in duration W from less than 1 ns to greater than weeks (more than 15 decades). Expressed as a phase space in “pseudo-luminosity” ($S_{\rm pk} D^2$, $D =$ distance) and a dimensionless time νW (with $\nu =$ radio frequency), the large ranges translate into effective radiation temperatures from non-thermal incoherent radiation up to $\sim 10^{12}$K for some AGNs, to much higher

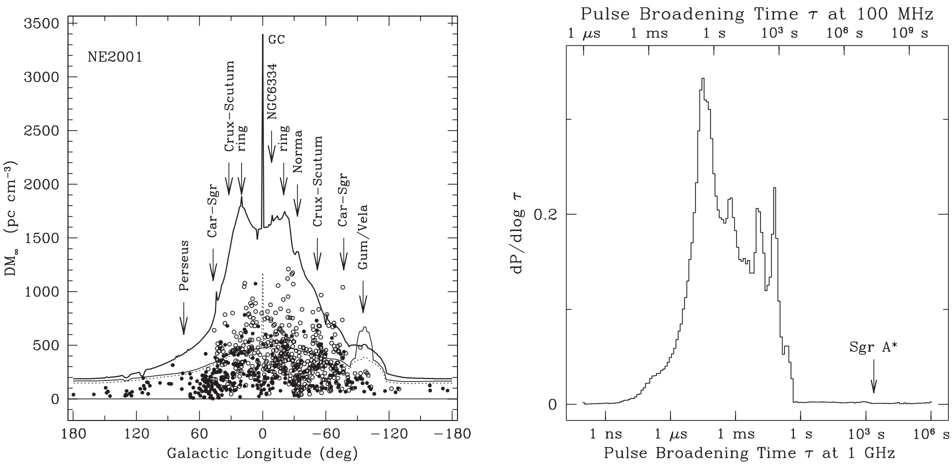

Figure 1. Left: Maximum dispersion measures DM_∞ predicted by the NE2001 electron density model for lines of sight integrated through the plane of the Milky Way. Right: Histogram of the pulse-broadening time expected from sources distributed throughout the disk of the Milky Way, defined as a disk of radius 10 kpc and thickness 1 kpc. The scattering measure and pulse broadening were calculated from the NE2001 model (Cordes & Lazio 2002). The bottom horizontal scale gives values for a radio frequency of 1 GHz and the top axis for 100 MHz.

temperatures for coherent sources such as molecular and plasma masers and pulsars. The record holder is a 0.4 ns shot pulse from the Crab pulsar with an effective temperature of 10^{42}K (Hankins & Eilek 2007). These large values illustrate the "bang for the buck" in creating radio photons with low amounts of total energy and the possibility that bright beacons await discovery from cosmological as well as Galactic sources.

3. Plasma Propagation Effects

Intervening plasmas dominate the effects that modify radio emission from both steady and time-dependent sources. Of course plasma effects are accompanied by gravitational lensing and redshift-dependent phenomena on cosmological lines of sight.

3.1. *Dispersion*

Fast transients have signal shapes modified by the strongly frequency-dependent travel time. When a pulse propagates dispersively its arrival time varies with frequency as $\Delta t = 4.15$ ms $\mathrm{DM}\nu^{-2}$ for dispersion measure DM (the line-of-sight integral of electron density) in standard units (pc cm^{-3}) and ν in GHz. Equivalently, the sweep rate in frequency is $\dot{\nu} \propto \nu^3 \mathrm{DM}^{-1}$. If uncompensated, a pulse measured across a finite bandwidth is smeared out. However, de-dispersion techniques are well developed, and enable this deterministic effect to be removed. DM is not known *a priori*, so trial values must be used from a set of plausible values. For Galactic sources DM ranges between 2.4 and $\sim$ 1500 pc cm^{-3} among known pulsars. The NE2001 model for free electrons in the Galaxy (Cordes & Lazio 2002) predicts dispersion measures up to about 3400 pc cm^{-3} for a direct sight-line through the Galactic centre. However, much larger values will obtain for lines of sight that pierce unmodelled dense HII regions. Fig. 1 (left) shows measured and modelled values of DM vs. Galactic longitude for directions through the plane of the Galaxy. The upper curve shows the maximum DM obtained from the NE2001 model.

Extragalactic sources will show contributions to DM from foreground Galactic electrons as well as from a host or intervening galaxy (if relevant) and from the intergalactic

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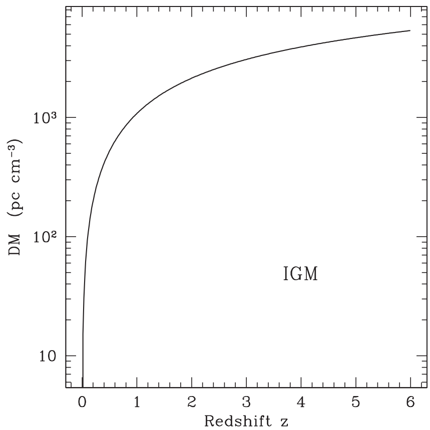

Figure 2. Dispersion measure from the intergalactic medium for a ΛCDM cosmology with $\Omega_{M\,0} = -0.27$, $\Omega_{b\,0} = 0.046$, and $H_0 = 70.4$ km s^{-1} Mpc^{-1}.

medium (IGM). The IGM contribution is

$$\mathrm{DM_{igm}(z) = cH_0^{-1} n_{e\,0} \int_0^z dz' \, \frac{(1+z')}{E(z')}}, \tag{3.1}$$

where $n_{e\,0}$ is the electron density from the baryonic fraction of the total closure density. A fiducial value for intergalactic dispersion is $\mathrm{DM_{igm}}_0 = cH_0^{-1} n_{e\,0} \approx 10^3$ pc cm^{-3}.

3.2. *Scattering and Scintillation*

Multipath propagation along Galactic lines of sight occurs because there is microstructure in the free electron density down to scales $\sim 10^3$ km (e.g. Rickett 1990) which diffracts and refracts radio waves. Relevant effects include angular broadening ("seeing"), pulse broadening and intensity scintillations.

Measured pulse broadening in Galactic lines of sight is as large as ~ 1 s but scales very strongly with frequency, $\tau_d \propto \nu^{-4}$. There are lines of sight with much larger predicted scattering times. Fig. 1 (right-hand panel) shows the distribution of τ_d expected from the electron-density model NE2001. On lines of sight to the Galactic centre, τ_d is thousands of seconds at 1 GHz and prohibits the detection of pulsars around Sgr A* at the conventional frequencies used in pulsar searches. Searches for fast transients from the Galactic centre region must therefore be done at high frequencies $\gtrsim 10$ GHz, where τ_d is $\sim 10^4$ times smaller.

Diffractive interstellar scintillation (DISS) results from interference between scattered wavefronts, and produces structure in both time and frequency with representative scales of 100 s and 0.1 MHz but with ranges in each of many orders of magnitude. Refractive scintillation (RISS) is caused by focusing and defocusing of radiation from scales much larger than those responsible for DISS in the strong-scattering regime. RISS is broadband, $\Delta\nu/\nu \sim 1$, and has time-scales of hours and longer, depending on the line of sight. RISS from Galactic plasma appears to underly the "intraday variability" (IDV) of some active galactic nuclei (e.g. Koay *et al.* 2011).

Broadening of pulses from extragalactic sources by intergalactic or extragalactic plasma has not yet been measured definitively. Propagation through a face-on intervening galaxy like the Milky Way would scatter radiation into ~ 1 mas at 1 GHz and broaden a pulse by a fiducial broadening time $\Delta t_{\mathrm{face\ on}} = \theta_s^2/2H_0 = 5\theta_{s,\mathrm{mas}}^2$ sec. Pulse broadening from any host galaxy of a transient source is deleveraged from this value by a geometrical factor

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$\sim H/D$, where H is the path length through the host galaxy and D is the distance. Pulse broadening could be much larger, however, from edge-on and starburst galaxies. If the IGM is turbulent (as is plausible) like the interstellar medium, then that too could make a sizable contribution. The detection of pulses from cosmological sources would represent a very powerful tool for probing the IGM, as would relatively nearby sources in local-group galaxies.

3.3. *Pulse Broadening Horizon*

Pulse broadening causes the detectability of fast transients to degrade over and above the effects of the inverse-square law. Pulses will not be selected if scattering broadening is larger than the intrinsic pulse width, W. From measurements of pulse broadening for pulsars seen at different distances we can define the *Galactic horizon* in terms of DM by requiring that $\tau_d \lesssim W$. For 1 ms pulses the horizon is ~5 kpc at 1 GHz, while 1 μs pulses can be seen to only 2.4 kpc at 1 GHz. These values apply only to sources within the Galactic disk. For a sight-line perpendicular to the disk, the seeing distance "breaks out" if it is more than ~1 kpc. At low frequencies such as 100 MHz, a $1-\mu s$ pulse can be seen only to ~100 pc.

The *cosmological horizon* can be calculated from the variation of DM with redshift z assuming that the IGM is completely ionized and that the relationship of pulse-broadening time to DM is the same as for Galactic sources—though that is at best a very crude approach. We find that a 1-ms pulse can be detected to $z \approx 0.2$ and that the broadening is $\tau_d \sim 100$ ms for transients originating at $z = 1$.

4. How Bright Can Fast Transients Be?

We already know that giant pulses from certain pulsars, like the Crab, are emitted frequently enough to be detectable at plausible rates out to 1.5 Mpc with the Arecibo Telescope. That number results from scaling 0.43 GHz pulses of amplitude $S_{\rm pk} \sim 200$ kJy that are pulse-broadened to ~ 100 μs duration and occur at a rate ~ 1 hr^{-1}. They correspond to a "pseudo-luminosity" $S_{\rm pk}D^2 \sim 10^{5.8}$ Jy kpc^2. Surely there are more luminous, giant-pulse-emitting pulsars that are detectable even further.

The case can be made that there are other burst sources that can tap larger sources of free energy than are available in pulsars like the Crab. They include:

• **Hyperfast rotators:** Pulsars born near the break-up limit (~ 1 ms) with canonical or magnetar-like magnetic fields (10^{12} to 10^{15} Gauss) can rapidly dump their rotational energy (using a moment of inertia of 10^{45} gm cm^2),

$$\frac{1}{2} I\Omega^2 = 2\pi^2 I P^{-2} \sim 10^{51.3}\,\mathrm{erg}\, I_{45} P_{\rm ms}^{-2}, \tag{4.1}$$

which is comparable to the non-neutrino energy released in a supernova. That energy will be released in a short amount of time as the pulsar rapidly spins down, but along the way it can drive giant-pulse emission much larger than seen from the Crab, perhaps by a factor of 10^6, e.g $S_{\rm pk}D^2 \sim 10^{12}$ Jy kpc^2. Such pulses could be seen out to ~ 1 Gpc.

• **Prompt GRB Counterparts:** The magnetospheres of neutron stars may reactivate when they merge, with orbital motion substituting for spin in generating voltage drops that accelerate particles and create electron-positron pairs (Hansen & Lyutikov 2001). NS–NS mergers are strong candidates for short-duration GRBs. The energy involved is similar to, or exceeds, that for extreme giant pulse-emitting objects. The GRB peak luminosity is fiducially $L_\gamma = 10^{51} L_{\gamma,51}$ erg s^{-1}. We assume that the true radio luminosity is a multiple ϵ_r of the gamma-ray luminosity, $L_r = \epsilon_r L_\gamma$. Over many kinds of astrophysical objects (stars, pulsars, AGNs), ϵ_r ranges from about 10^{-8} (Crab pulsar) to

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10^{-3} (blazars). We estimate the pseudo-luminosity L_p in units of Jy kpc^2 by calculating the peak radio flux from the GRB assuming (only fiducially) isotropic emission. Beaming may influence the radio luminosity estimate as it does the gamma-ray luminosity. This approach gives a stupendously large pseudo-luminosity and peak flux density,

$$L_p = 10^{15.9}\,\mathrm{Jy\,kpc^2}\left(\frac{\epsilon_{r,-5}L_{\gamma,51}}{\Delta\nu_{r,\mathrm{GHz}}}\right), \qquad S_{\mathrm{pk}} = 10^{2.9}\,\mathrm{Jy}\left(\frac{\epsilon_{r,-5}L_{\gamma,51}}{\Delta\nu_{r,\mathrm{GHz}}}\right)\left(\frac{3\,\mathrm{Gpc}}{d_L}\right)^2. \quad (4.2)$$

where we use a fiducial value $\epsilon_r = 10^{-5}\epsilon_{r,-5}$ and a radio emission bandwidth $\Delta\nu_r = 1$ GHz $\Delta\nu_{r,\mathrm{GHz}}$.

5. Transient Surveys: Fast and Slow

Pulsar Survey pipelines with time sampling of 50 to 100 μs now routinely include analysis for single bursts, which led to the discovery of RRATs. Analysis of archival data, such as Very Large Array data, has aimed to identify slow transients. Planning for new telescopes and those coming on-line—such as the EVLA, LOFAR, ASKAP, LWA, MeerKAT and the SKA—now includes transients as key science.

6. Energetics vs. Information

In many circumstances radio luminosities represent a trivial amount of the total power budget of a source. However, there are exceptions; in long-period pulsars the luminosity is in fact more than a few per cent of the spindown loss rate $\dot{E} = I\Omega\dot{\Omega}$. More importantly, in many cases radio wavelengths have provided crucial, unique information about high-energy and potential gravitational-wave sources, in part because radio photons are easily produced. The discovery of "intermittent" pulsars (Kramer *et al.* 2006) indicates that radio emission traces the overall spindown energy losses from spin-driven pulsars. Intermittent pulsars include cases where radio emission shuts off for long periods (10^6 s) and is on for only a fraction of that time. During the "on" period, $\dot{E}$ can be tens of percent larger than during the "off" period. The situation may be similar in a host of other objects which, owing to beaming, may be quiet in high-energy bands but quite loud in others. GRB orphan afterglows have been seen (e.g. Soderberg *et al.* 2010), but prompt emission may also occur without any counterpart GRB (Cordes 2007).

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