FAST RADIO BURST FOLLOW-UP WITH THE *SWIFT* X-RAY TELESCOPE

Abstract

Fast radio bursts (FRBs) are millisecond radio pulses of unknown extragalactic origin that are normally de-dispersed so as to associate all frequencies to a single common time. However, if instead the pulses are interpreted as a series of coherent self-similar signals at different frequencies, then the theory of quark novae (QNe) can explain FRBs. Here, the core of a long-period neutron star collapses into a quark star, releasing a relativistic shell of r-process elements that undergo β-decay and produce electrons that emit synchrotron radiation upon reaching the light cylinder of the parent neutron star. The observational consequence is a prompt FRB, followed by electron recombination with the surrounding weakly ionized medium and emission in the few keV range lasting roughly 80 s. We propose to follow-up 10 new FRBs that are detected with CHIME/FRB using the *Swift* X-ray telescope. We are requesting 1 hour of Highest Priority Target of Opportunity time.

1 Science Justification

In 2007, a 30 Jy radio pulse of duration less than 5 ms and dispersion measure (DM) 375 cm^{-3} pc was found in archival data from a survey of the Large Magellanic Cloud with the Parkes radio telescope in Australia (Lorimer et al. 2007). Since then, this fast radio burst (FRB) phenomenon has been confirmed by several other radio telescopes around the world, primarily around 1.4 GHz (Thornton et al. 2013; Petroff et al 2015; Bannister et al. 2017; Shannon et al. 2018). Among the FRBs published to date, all are consistent with extragalactic sources, owing to their DM that exceeds what would be contributed by the Milky Way according to NE2001 simulations (Cordes & Lazio 2002). The most up-to-date record of published FRBs is maintained at the FRB catalogue webpage[1], a list of 52 events of which just one is a repeating event (Spitler et al. 2016; Scholz et al. 2016).

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) FRB project will detect FRBs in real-time at an estimated rate of 2-42 detections per day in the 400-800 MHz range (CHIME/FRB Collaboration 2018). A detection software pipeline is in place and the virtual observatory event (VOEvent) network will be used to broadcast CHIME/FRB events. The VOEvent network allows for real-time distribution and collection of an FRB detection in the form of a standardized concisely formatted data packet called a VOEvent. The VOEvent contains the telescope parameters (beam semi-major/minor axes, central frequency, gain), the FRB parameters (DM, SNR, and flux), and the IVOA Space-Time Coordinates (STC) on the celestial sky. These parameters are just enough to inform the receiving telescope of where and when to point for a follow-up observation of the initial FRB detection (Petroff et al. 2017). Once a new FRB is detected, the VOEvent will be issued by CHIME and received by *Swift* within seconds to minutes.

The quark nova (QN) hypothesis for FRBs as put forth by Shand et al (2016) will be described presently to motivate the need for X-ray follow-up observations of new FRBs. In the model, isolated aging neutron stars (NSs) whose stellar progenitors had masses $10-20M_{\odot}$ undergo spin-down through magnetic dipole radiation until the core is dense enough to initiate quark deconfinement, following which accretion and s-quark seeding causes an explosion that ejects an outer layer of neutrons (Ouyed et al. 2002; Staff et al. 2006; Ouyed et al. 2013b). The ejected neutrons produce unstable heavy nuclei (Keränen et al. 2005; Ouyed & Leahy 2009) that undergo β-decay in the expanding spherical ejecta, producing electrons that are accelerated along the strong magnetic field present at the parent NS's light cylinder (LC). The synchrotron radiation produces the prompt FRB. Lastly, the emitted electrons recombine with the weakly ionized plasma in the surrounding medium and promptly produce photons in the keV range.

The FRB time spectrum is extended to the order of seconds because the ejecta sphere sweeps across an increasing latitude of the LC, and the time profile is exponential with a millisecond duration in connection

[1]See https://frbcat.org for an up-to-date list of FRBs

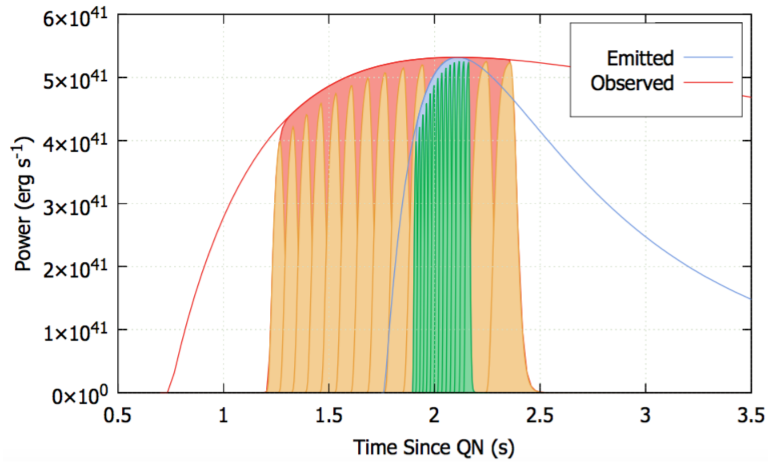

Figure 1: Dispersion due to intervening cold plasma modifies the pure FRB signal (red) and produces the observed signal (blue). For bandwidth-limited measurements in 25 MHz sub-bands, the green and orange pulses exhibit the characteristic millisecond pulse duration and their filled portions indicate the power seen in those bands. [Adapted from Figure 1 in Shand et al. (2016)]

with the β-decaying nuclei. In order for the QN model to be correct, it must also be insisted that the de-dispersion convention of associating all frequency channels to a single common time is an error: instead, the QN model suggests that the pulse is truly on the order of seconds long and still dominated by cold plasma dispersion. Namely, electrons are produced from the decaying nuclei in a continuous series of bunches so that coherent pulses at each frequency are emitted over several seconds, or hundreds of milliseconds for bandwidth-limited measurements (see Figure 1). That this QN model for FRBs is worth believing is demonstrated in its successful application to FRB 110220, as shown in Figure 2. The model is even capable of predicting a more accurate DM; namely, the magnetic field at the LC transitions from dipolar to monopolar at the equatorial plane of the NS, and causes the radiation at this angle to be much fainter, leading to a maximum observable frequency of

$$\nu_{\max} = \kappa_\nu \gamma^2 B_0 \left(\frac{2\pi r_0 \cos\phi}{cP} \right)^2 \tag{1}$$

where κ_ν is a constant (see Lang 1999)[2], B_0 is the NS surface magnetic field strength, r_0 is the NS radius, P is the NS period, γ is the Lorentz factor of the electrons, and ϕ is the latitude angle on the LC. Given a spectral flux at each frequency, one can find the DM, and for FRB 110220 one finds a DM of 725 cm^{-3} pc instead of 944 cm^{-3} pc. Shand et al (2016) estimate a rate of QN-FRBs and find approximately 3 per thousand year per galaxy which is consistent with the observed FRB rate so far; further, they suggest that if the QN model is correct, the conversion of an old neutron star of period $1 - 10$ s to a QS of magnetic field 10^{15} Gauss implies that the corresponding region on the $P\dot{P}$ diagram of NSs is populated by QS and not magnetars.

In summary, the QN model makes an observable prediction in X-ray and its predictions agree with at least one FRB and in general with the rate. There is plenty of evidence for magnetars in our galaxy (Olausen & Kaspi 2014), thus if the QN model is correct it lends credence to the occurence of QN-FRBs in other galaxies. For these reasons it is appropriate to investigate new FRB events for X-ray follower counterparts as a means to understand these enigmatic radio transients.

[2]Remark: For a $P = 1$ s, $B = 10^{14}$ Gauss NS, need $\kappa_\nu \approx 10^{14}$ Hz Gauss^{-1} for peak frequency to be in X-ray

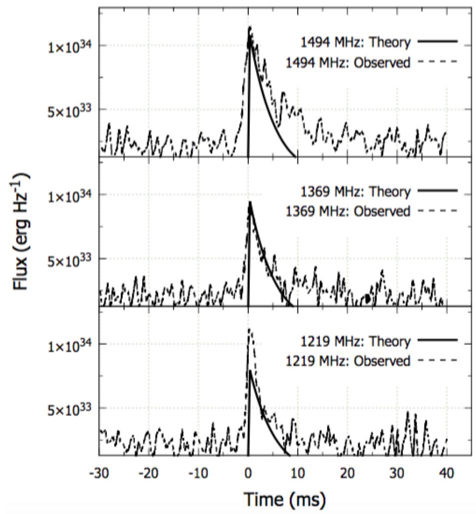

Figure 2: The flux predicted from the QN model (Eq. 15 in Shand et al. 2016) is fit to select frequencies from the spectrum of FRB 110220 using reasonable parameters (Table 1 in Shand et. al 2016); no statistical "best-fit" is done, but the prediction already matches quite well. [Adapted from Figure 8 in Shand et. al (2016)]

2 Technical Justification

The estimate for the amount of observing time needed to follow-up a new FRB follows a basic line of reasoning: the estimated length of time that the X-ray emission from the quark nova lasts is on the order of 80 s (Ouyed & Sannino 2002), and it seems reasonable to suggest at least an hour of an observing period to get close to the blind-search sensitivity of *Swift* of 10^{-13} ergs cm^{-2} s^{-1} at 10^4 s. The X-ray flux predicted from quark nova is expected to be faint and the suggested integration time should be long enough to be sensitive to the event.

Because of the minute-timescale duration of the X-ray signal that is predicted to follow the initial FRB that CHIME/FRB will detect, our observation request requires the High Priority (level 1) Target of Opportunity classification so as not to miss the signal. Once the FRB is detected by CHIME/FRB, a VOEvent will be issued that can be received by ground-based *Swift* X-ray telescope (XRT) computers and sent via telemetry to the space telescope within a few seconds. The spacecraft will then need to slew to point in the direction of the FRB which is known to require between 20 and 70 s, indicating that all of the detected FRBs can be followed-up in time. Given that the VOEvent network is in place we feel the minimal latency in our coordination effort warrants awarding our campaign the Level 1 ToO priority.

On March 14 of 2018, an observing campaign similar to what we are requesting was carried out for FRB 180311[3] presumably by the research team that discovered this (so-far unverified) FRB with the Parkes radio telescope in Australia. The priority level in this case was much lower (level 3) and the observations were five isolated segments lasting about 1000 s each, for a total campaign of about 1.4 hours. While the efforts were likely different than the current present proposal, this appears to be one of only two others made for *Swift* XRT follow-ups of FRBs, and it is handy to as a reference for our proposal. In our case, our broadcasted VOEvent for the CHIME/FRB event will contain all of the necessary information for making a logical decision in a punctual time, so again our proposition should be considered for a higher priority than previous FRB follow-up proposals.

Tools for receiving VOEvents and parsing the standardized XML documents they contain are freely

[3]https://www.swift.psu.edu/operations/obsSchedule.php?t=10603&s=2

available online. The VOEvent structure is standardized and already being issued for gamma ray burst (GRB) detections and will eventually be used for gravitational wave detection by the Laser Interferometry Gravitational wave Observatory (LIGO). If the service is not already in place for *Swift*, the process to do so is simple and would likely prove useful for the future of *Swift* as the popularity of distributing via the VOEvent network grows. Seeing as FRBs occupy centre stage in the radio community and CHIME/FRB will likely be the main player in FRB detections, the successful triggering of other detectors for multi-wavelength studies will place a lasting impact on the astrophysical community in general.

As an example of how the VOEvent service promises to be a practical (though potentially unconventional) way to inform *Swift*, the LOFAR transient buffer boards (TBBs) are currently being triggered by the Effelsberg 100m telescope on potential FRBs detected at 1.4 GHz. A prompt FRB VOEvent is sent and LOFAR reacts within seconds to stop TBB acquisition, and then waits for a special "update" VOEvent that comes at a later time with RFI-cleaning applied to the FRB so that LOFAR can decide whether to dump TBB data or not. Since this process involves some 5 TBs of data and takes 30 minutes, the update event is crucial. (See Petroff et al.(2017) for this and other accounts of FRB VOEvent usage.)

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