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/S174392131200110X

Optical Pulsations from Isolated Neutron Stars

Roberto P. Mignani[1,2]

[1]Mullard Space Science Laboratory, Dorking, Surrey, RH5 6NT, UK
email: rm2@mssl.ucl.ac.uk

[2]Kepler Institute of Astronomy, University of Zielona Góra, Zielona Góra, Poland

Abstract. Because they are fast rotating objects, isolated neutron stars (INS) are obvious targets for high-time-resolution observations. With the number of optical/UV/IR INSs detections now at 24, timing observations become increasingly important in INS astrophysics.

Keywords. stars: neutron; pulsars: general; radiation mechanisms: general

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24 INSs have been detected in the UV, optical, and IR (Mignani 2011). As well as pulsars, they include the magnetars (Mereghetti 2008) and the X-ray Dim INSs (XDINSs; Turolla 2009). Optical timing (see Mignani 2010a) yields the direct INS identification, input for models of neutron-star magnetospheres through comparisons of multi-wavelength light curves, evidence of debris disks, the spin-down parameters of radio-silent INSs, and measurements of giant pulses—only detected in the radio and optical (Mignani 2010b, c). This paper focusses on classes for which counterparts have been detected; it describes the optical pulsation emission mechanisms and the observational challenges in timing studies of INSs, and outlines the characteristics of pulsations from pulsars and magnetars.

1. Optical Pulsations: Mechanisms and Observations

The production of optical pulsations from INSs depends on the underlying emission process. In some cases, the optical emission is the result of energy irradiation from relativistic particles in the neutron-star magnetosphere through synchrotron losses or other non-thermal processes. Optical pulsations are, then, expected from INSs which have a strong magnetospheric activity, i.e., pulsars and magnetars. In those cases, the optical emission is produced near the magnetic poles, yielding a small beaming factor. Indeed, optical pulsations are mostly characterised by sharp, double-peaked profiles. Phase shifts with respect to the X-ray and gamma-ray light curves are usually observed if the emission comes from different regions in the magnetosphere with (for instance) the gamma-ray emission being produced in the outer magnetosphere.

In some other cases, the optical emission is of thermal origin and is produced by the cooling of the neutron-star surface. Optical pulsations are therefore expected from INSs with dominant thermal emission components, e.g., the XDINSs, if the optical emission is associated with a non-isotropic temperature distribution on the neutron-star surface. In that case, optical pulsations are expected to have shallow profiles, while phase shifts between the optical and X-ray light curves are a natural consequence of the emission being produced from regions of different temperature on the neutron-star surface.

Finally, it is possible that optical pulsations do not originate directly from the neutron star's magnetosphere or surface but from the reprocessing of the pulsed X-ray radiation in a circumstellar debris disk, formed out of fall-back material after the supernova explosion. In that case, optical pulsations can be produced from any type of INS with a disk. The reprocessing affects the optical light curve, with wider profiles expected with respect to the X-ray one owing to the smearing of the X-ray pulse by the disk material. Moreover, phase shifts are expected between the optical and X-ray light curves, and are due to the radiation travel-time between the neutron star and the disk and typically depend on the size of the disk inner radius and geometry. Depending on the disk viscosity, a continuum emission component, produced by the X-ray reprocessing, can be present, and might be stronger than the pulsed one.

2. Optical Pulsars: Challenging Targets

Only 8 of the 24 INSs detected at optical wavelengths (Mignani 2011) are also detected as optical pulsars. There are several reasons for this paucity. One is related to characteristics of their optical emission and to their intrinsic faintness, which limits the search for a periodicity: only three INSs are brighter than $V \sim 25$. Moreover, the value of the Pulsed Fraction (PF) depends on the underlying emission process and it is difficult to determine it *a priori* without knowing the nature of the optical emission, i.e., without adequate spectral information. The latter is usually obtained through multi-band photometry measurements which are sometimes collected over several years. At the same time, the value of the PF measured at other wavelengths, e.g., in the X-rays, cannot be taken as an absolute reference since light-curve profiles vary significantly as a function of wavelength, very much like the INS spectrum. The slope of the optical spectrum and/or the extinction along the line of sight also biasses the choice of the observing wavelengths which, in turns, has to cope with the availability of a detector/instrument working in that wavelength range. Moreover, as observed (e.g., in the magnetars), the PF depends very much on the source brightness, varying significantly from active to quiescent states.

Difficulties of running periodicity-search algorithms also contribute. The low number of photons which can be collected over integrations that are a few hours long makes it impossible to analyse the time series through a Fast Fourier Transform (FFT). Thus, one needs to fold the time series around a reference period available from radio, X- or gamma-ray observations. In this case, the INS must be a stable rotator: it must now feature sudden variations of the spin-down rate (glitches), otherwise the search for pulsations would require contemporary ephemeris. A further difficulty is in the *a priori* estimate of an expectation value for the PF, and thence of the required integration time.

A further reason is related to the availability and characteristics of the instruments used for optical timing. For instance, for a given object one can expect a higher flux (e.g., in the IR than in the UV) depending on the spectrum and extinction. Pulsations might thus be undetectable outside an optimised wavelength range, which implies an instrument/detector selection effect. Moreover, the timing of fainter INSs became feasible only in the late 1990s with the advent of 8-m-class telescopes like the VLT or Gemini. Even in those cases, however, the search for optical pulsars clashed with the paucity of on-site instruments for high-time-resolution observations, either photon counters, time-resolved imagers or fast read-out windowed CCD devices. HST was equipped with instruments for high-time-resolution observations in the optical/UV but for various reasons they have not been available to users. Most timing facilities on ground-based telescopes are guest instruments, built, maintained and operated by private consortia and not directly available to the community for open-time proposals. Moreover, they are not easily portable, have to be properly interfaced to different telescope structures and hardware, and the instrument shipping adds non-negligible costs to travel expenses both for equipment and manpower.

3. Pulsars and Magnetars

So far, five of the 12 identified pulsars also pulsate in the optical. In general, pulsars are the best target INSs for optical timing since they usually count on accurate radio ephemeris, spin-down parameters, distances and positions, with many potential targets routinely discovered in radio and gamma-ray surveys. Moreover, many pulsars are observed in X-rays, which gives the interstellar extinction via the $N_{\rm H}$ and thence an estimate of the brightness and of the most-suited observing wavelength. In general, optical light curves of pulsars are all double-peaked, with a phase separation $\Delta\phi = 0.4$–0.6, the only exception being B0540–69 for which $\Delta\phi \sim 0.2$. The peaks in the optical light curve are not always in phase with the gamma/X/radio ones, as expected if the pulse originates in different regions of the magnetosphere. All pulsars except B0540–69 are also detected as optical/UV pulsars, but only the Crab is detected as an IR pulsar as well. Interestingly, one of the very few measurements of a pulsar braking index has been obtained from the optical timing of B0540–69 (Gradari *et al.* 2011), while the Crab is the only pulsar where giant optical and radio pulses have been observed simultaneously (see p. 296).

Three out of 6 magnetars identified in the optical/IR pulsate. Their emission is either of magnetospheric origin, perhaps powered by the magnetic field, or is produced by X-ray reprocessing in a debris disk (Mignani 2011 and references therein). In all cases, the profile of the optical pulsation reproduces the X-ray one. For 1E 1048.1–5937, the optical PF is ~70% of the X-ray one, providing evidence for disk reprocessing. However, there is also a marginal evidence (2σ) for X-ray lags, which is not expected in the reprocessing model. For 4U 0142+61 the optical PF is larger than the X-ray one and there is evidence (2σ) of optical lags. For SGR 0501+4516 the optical PF is a larger than the X-ray one, and the optical light curve is in phase with the X-ray one.

4. Future Perspectives

The wealth of pulsating INSs detected in X-rays (~60) and gamma-rays (~80) highlights a quantitative gap between the UV/optical/IR (8) and high-energy domains. The huge collecting areas of the Extremely Large Telescope (ELT) together with new generation instruments is needed to start a new era in optical timing (Mignani 2010b, c) and to match the potentials of the LOFT X-ray mission (p. 372). QuantEYE, the first pilot study for the OWL 100-m telescope, was based on quantum detector technology to reach pico-s time resolution (p. 280). QuantEYE was father to prototypes for the Asiago 182-cm telescope (AqEYE) and for the 3.6-m NTT (IquEYE), which produced the best measurements of pulsar light curves. A new prototype (EquEYE) is now being studied for the VLT as a possible precursor for a new quantum photometer for the E-ELT. That will open a new era in optical-timing studies of isolated neutron stars.

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https://doi.org/10.1017/S174392131200110X Published online by Cambridge University Press