Astron. Astrophys. 342, L5–L8 (1999)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Radius and distance estimates of the isolated neutron stars Geminga and PSR B0656+14 using optical photometry

A. Golden[1] **and A. Shearer**[2]

[1] Department of Physics, National University of Ireland, Galway, Ireland
[2] Information Technology Centre, National University of Ireland, Galway, Ireland

Received 2 October 1998 / Accepted 10 December 1998

Abstract. Integrated ground-based and HST optical studies of isolated neutron stars have provided important independent datasets in the determination of emission activity, particularly in the fitting of anticipated Rayleigh-Jeans extrapolations from EUV/soft X-ray datasets, despite their intrinsic faintness. Differentiation of the pulsed and unpulsed fluxes and consequently of the nonthermal and thermal modes of emission could provide definitive data with which to constrain this blackbody continuum. Based upon high speed photometric observations of Geminga and PSR B0656+14 in the B band, we have combined upper limits of unpulsed emission with recently published model-fits with a view to assessing possible implications for the R/d parameter. For Geminga, with a known distance of $\sim$ 160 pc, we find that $R_\infty \leq 9.5$ km for a $\sim$ blackbody source, and $R_\infty \leq 10.0$ km with the presence of a magnetized H atmosphere. In addition, we suggest that PSR B0656+14 is some $\sim$4–5 times closer than the 760 pc estimated from DM measurements alone.

Key words: stars: pulsars: individual: Geminga, PSR B0656+14

1. Introduction

Uncertainty regarding the behaviour of nuclear matter in the deep neutron star interior has compromised a complete description of the dense matter equation of state (EOS). Various theoretical models in circulation predict a range of macroscopic observables, such as masses, radii, temperatures and maximum rotation rates, and as such are open to scrutiny with empirical data. Relativistic effects complicate such observations, with the true radius, R, related to the *apparent* radius at a distance (d $\rightarrow \infty$) as

$$R_\infty = (1+z)R = R/\sqrt{1-2GM/Rc^2}, \quad (1)$$

with M being the mass of the compact object, and z the associated gravitational redshift. Theory to date indicates that 7km $< R_\infty <$ 20km, dependent on the stiffness of the EOS (e.g. Lindblom 1992). Binary studies suggest a common value of neutron star mass approximately that of the canonical estimate of 1.4 $M_\odot$ (Van Kerwijk et al. 1995). Typically, the model neutron star is assumed to have $M \sim 1.4\ M_\odot$ and $R_\infty \sim$ 13km ($R \sim$ 10 km). Based on observations of the neutron star's thermal emission in the extreme UV (EUV) and soft X-ray bands, it should in principle be feasible to compute the ideal blackbody spectral energy distribution (SED) as a function of ($T_{\rm surface}$, $N_{\rm H}$ & R/d), and for a known distance d, an estimate of the apparent neutron star radius. It is generally agreed that such a measurement would have a profound impact in constraining EOS models. However, strong galactic HI absorption at these wavelengths restricts observations to the closest neutron stars, and uncertainty in X-ray detector sensitivities at these low ($\leq$ 0.2 keV) energies (e.g. Walters & An 1998) has compromised attempts to accurately determine estimates for $N_{\rm H}$ and $T_{\rm surface}$. Furthermore, such an analysis may be complicated by neutron star phenomenology, such as atmospheric opacity effects, an active magnetosphere, hot polar cap regions and accretion processes. It is critical to separate the various contributions, so as to estimate the genuine total surface component. For the older, isolated neutron stars (INS), phase-resolved studies in the soft X-ray, EUV and optical wavebands can provide such a SED, and thus a real possibility of determining R_∞. The Rayleigh-Jeans tail in the optical regime provides stringent constraints to any SED model-fit, and in this waveband atmospheric opacity effects are expected to have the most noticeable impact. In the X-ray regime where the blackbody continuum peaks, low Z atmospheres preferentially transmit radiation from the lower, hotter regions of the photosphere, producing a X-ray spectrum suggestive of a 'hotter' source (Romani 1987). The Rayleigh-Jeans tail is unaffected by this deviation, and discrepancies between optical spectrophotometry and higher energy extrapolations may be rigorously tested (Pavlov et al. 1998). However the intrinsic faintness of these astrophysical objects in the optical regime coupled with the limitations of current technology have restricted previous optical studies to deep integrated photometry. These observations have in some ways aided such

Send offprint requests to: A. Golden (agolden@physics.ucg.ie)

thermal continuum studies (e.g. Walters & Matthews 1997), but the differentiation of pulsed (predominantly nonthermal) and unpulsed (thermal) components would be ideal in a more rigorous treatment. Recently, the TRIFFID high speed optical photometer detected pulsations in the B band from the optical counterparts of the middle aged pulsars Geminga and PSR B0656+14 (Shearer et al. 1997, Shearer et al. 1998). Both light curves are highly pulsed and suggest a dominant nonthermal mode of emission optically. Despite their extreme faintness, it was possible in both cases to determine upper limits to each pulsar's thermal component of emission. In this letter, we combine these unpulsed limits with the results of recently published ground-based and HST photometric analysis on these two pulsars (Pavlov et al. 1997, Martin et al. 1998 hereafter $PWC97$ & $MHS98$), and derive radius/distance estimates for both. In particular, for the case of Geminga with a known parallax distance of ~ 160 pc, we provide for the first time an upper limit for R_∞ based upon such phase-resolved photometry.

We approach the analysis of the optical photometry by assuming a model fit incorporating both nonthermal power-law and thermal components of emission in the UBVRI regime, as originally adopted by $PWC97$. This two-component model fit is defined as:

$$f(\nu) = \left[f_0 \left(\frac{\nu}{\nu_0} \right)^{-\alpha} + g_0 \left(\frac{\nu}{\nu_0} \right)^2 \right] \times 10^{-0.4A(\nu)} , \qquad (2)$$

with $\nu_0 = 8.766 \times 10^{14}$ Hz an arbitrary reference frequency, and $A(\nu)$ the interstellar extinction determined following Savage & Mathis (1979). g_0 and f_0 are taken to be the values of the nonthermal and thermal fluxes at $\nu = \nu_0$. The latter can be expressed, for the chosen value of ν_0, as

$$g_0 = 3.116 \times 10^{-31} G \, \frac{\mathrm{erg}}{\mathrm{cm^2\ s\ Hz}} , \qquad G \equiv T_6 \left(\frac{R_{10}}{d_{500}} \right)^2 \quad (3)$$

where $T = 10^6 T_6$ K is the apparent neutron star brightness temperature, $R_\infty = 10 R_{10}$ km the radius and $d = 500 d_{500}$ pc the distance to the blackbody. Model fits for both pulsars have suggested the presence of both emission modes, yet uncertainty in the optimum ($T_{\rm surface}$,$N_{\rm H}$, R/d) solution based on EUV/soft X-ray datasets restricts accurate differentiation. By providing upper bounds for the unpulsed flux, and indirectly $N_{\rm H}$ via the estimated $A(\nu)$ towards the pulsar, we can derive an *independent* estimate of G and in this way, constrain ($T_{\rm surface}$, R/d) space. The use of the lower bounds to $T_{\rm surface}$ for a given neutron star would then yield *upper* bounds to the R/d parameter.

2. Geminga

PSR 0633+17, or Geminga, provides one of the most ideal neutron stars for such an analysis, as HST observations have determined its distance by parallax to 159^{+59}_{-34} pc (Caraveo et al. 1996). However, it is by no means clear precisely what the nature of its emission processes are, despite considerable observational efforts from the optical to γ-rays. Original ROSAT observations suggested dominant thermal emission from the surface modulated by a hotter polar cap (Halpern & Ruderman 1993), although later observations especially those of *ASCA* indicated the emission was thermal and nonthermal in origin (Halpern & Wang 1997). Disagreement remains on the optimum SED fits to data from ROSAT, EUVE and ASCA with the pulsar's surface temperature within $(2.5\text{–}6) \times 10^5$ K. There have been further suggestions that the pulsar's thermal emission is strongly affected by magnetospheric cyclotron resonance blanketing (Wang et al. 1998), which would severely compromise any estimate of the *true* neutron star surface temperature. Optical observations suggest an unusual SED, with deviations in the expected functional form, possibly as a result of ion cyclotron absorption/emission processes. The most recent of such observations ($MHS98$), made using the Keck LRIS, spanned 370-800 nm and yielded a flat power law shape ($f_\nu \propto \nu^{-0.8}$) and a noticeable broad dip at 630-650 nm with perhaps a slight modulation at V, B & I as advanced by Bignami et al. (1996). The composite power-law may be fitted by either a combined blackbody and power-law (i.e. nonthermal emission with $\alpha \sim 1.9 \pm 0.6$) or a blackbody plus global ion cyclotron emission. The former model is undoubtedly the most likely, following the discovery of a highly pulsed lightcurve in the B band (Shearer et al. 1998). Fig. 1. shows the model-fit spectrum of $MHS98$ with the results of Shearer et al. (1998).

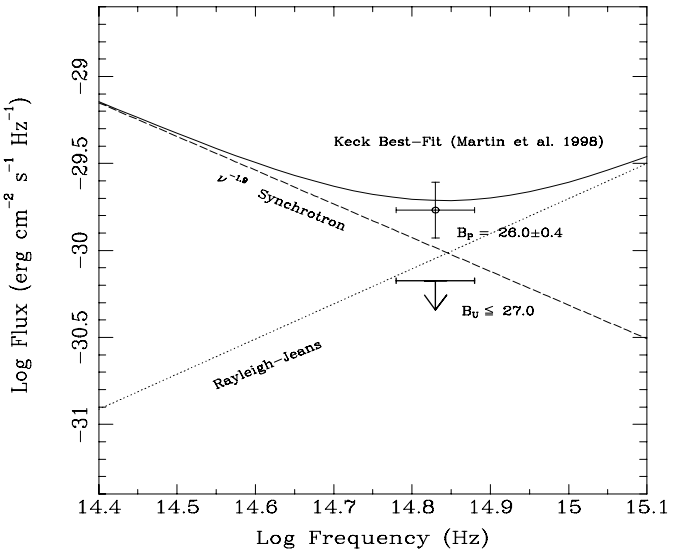

Fig. 1. Keck LRIS Optical spectrum of Geminga, with best-fit two component model of Martin et al. (1998) and TRIFFID/BTA pulsed and unpulsed flux estimates in B (Shearer et al. 1998)

A value of G = 4.4 is obtained by applying a solution in the form of (3) to the best-fit Keck observations of $MHS98$, setting A(ν) ~ 0 due to the pulsar's close proximity. Introducing our independently estimated unpulsed upper limit in the B band of 6.77×10^{-31} ergs cm^2 s^{-1} Hz^{-1}, we conclude with $G \leq 3.6 \pm 0.1$, allowing errors in G for the spectral response of the MAMA/B-filter combination. The decrease can be inferred as either a reduction in the emission area or a drop in $T_{\rm surface}$ ($d \sim 160$ pc). As a consequence, one expects the non-

thermal component to increase proportionately in the original model fit, if this unpulsed estimate is representative of a general surface based thermal emission. If we assume that $T_{\rm surface}$ remains unchanged, then the obvious conclusion is that R has been overestimated. In fact, using $G \leq 3.6$, $T_{\rm surface} \sim 4.0 \times 10^5$ K (MHS98) and $d = 159^{+59}_{-34}$ pc suggests $R_\infty \leq 9.5^{+3.5}_{-2.0}$ km for a $\sim$ blackbody source (indistinguishable from a Fe/Si atmosphere – see Pavlov et al. 1998). An alternative explanation for the change in G could be understood under the assumption of atmospheric opacity effects for the total surface thermal emission at X-ray energies. As $PWC97$ point out, there is no ideal way to reconcile the actual brightness temperature with the estimated X-ray $T_{\rm surface}$. Fits with magnetized ($\sim 10^{12}$ G) H atmospheres suggest that a spectrum in the optical regime can be fitted as a Rayleigh-Jeans tail with $T_{\rm surface} = 0.9 T_{\rm eff}$ ($PWC97$). Applying this correction yields $R_\infty \leq 10.0^{+3.8}_{-2.1}$ km.

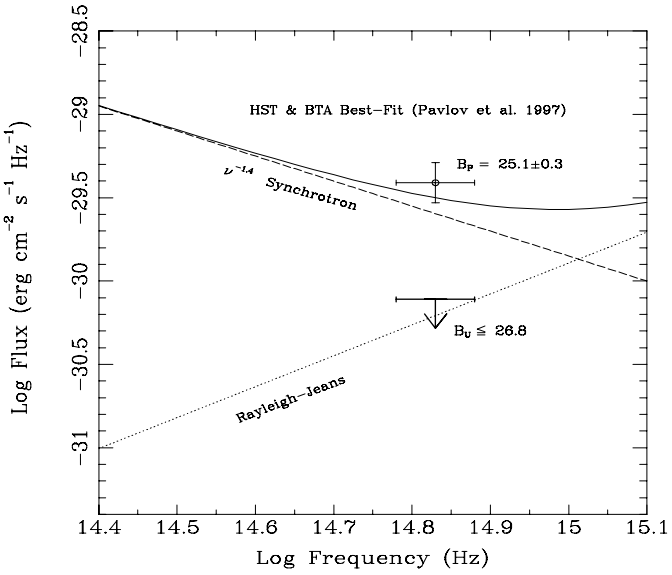

Fig. 2. HST & 6m BTA based photometry and best-fit two component model of PSR B0656+14 for the colour excess $E(B-V)$ = 0.03 (Pavlov et al. 1997), with TRIFFID/BTA pulsed and unpulsed flux estimates in B superimposed (Shearer et al. 1997)

3. PSR B0656+14

An extensive literature exists devoted to the analysis of EXOSAT, ROSAT and EUVE observations of the pulsar PSR B0656+14. The consensus is of thermal emission from the surface, modulated by emission from a hot polar cap and from nonthermal activity in the magnetosphere. However, its distance estimate is by no means exact ranging from $\sim$ 100 to 760 pc (Caraveo et al. 1994) – the latter based upon a DM fit to the uncertain galactic electron model in this vicinity (Taylor et al. 1993). Applying a common distance estimate of $\sim$ 500 pc, a range of solutions are possible in ($T_{\rm surface}$, $N_{\rm H}$) space assuming the canonical model, and this is reflected in the literature, with $T_{\rm surface}$ = (3–9)$\times 10^5$ K and $N_{\rm H}$ = (0.5–2.0)$\times 10^{20} cm^2$ (Finley et al. 1992, Anderson et al. 1993, Greiveldinger et al. 1996). Early limited observations using the NTT (Caraveo et al. 1994) and the HST (Pavlov et al. 1996) indicated that the optical counterpart's emission was predominately nonthermal in nature, and a subsequent two-component model fit to detailed HST and ground-based photometry spanning the UBVRI regime by $PWC97$ substantiated this assessment – although the detection of highly pulsed emission in the B band (Shearer et al. 1997) from the optical counterpart unequivocally confirmed this hypothesis. The upper limit on the unpulsed flux from the resulting lightcurve was estimated to be 8×10^{-31} ergs cm^{-2} s^{-1} Hz^{-1}. Fig. 2. shows the $PWC97$ model fit with these pulsed/unpulsed fluxes.

$PWC97$ fitted the observed UBVRI spectrum with a two-component model following the formalism of (2) and (3). Applying the interstellar extinctions determined for the three estimated colour excesses towards the pulsar of $E(B-V)$ = 0.01, 0.03 and 0.05 yielded best fit values of G = 3.0, 3.7 and 4.3 respectively. Taking $g_0 = 8 \times 10^{-31}$ ergs cm^{-2} s^{-1} Hz^{-1}, (2) may be rearranged in terms of G, and solved for the three $E(B-V)$ estimates, concluding with G = 4.4, 4.8 and 5.2 (all $\pm$0.1). respectively. An increase of this G parameter is consistent with either an increase in the expected $T_{\rm surface}$, emission area or a decrease in the pulsar's distance.

In terms of previous model fits, G ranges from 0.9 (Finley et al. 1992), 2.1 (Greiveldinger et al. 1996) to 2.6 (Anderson et al. 1993), the latter incorporating a magnetised ($\sim 10^{12}$ G) H atmosphere. As observations have accrued, and uncertainties in X-ray detector sensitivities have been addressed, the trend has been a decrease in the derived surface temperature, from $\sim 9.0 \times 10^5$K to $\sim 5.0 \times 10^5$K. Recent work by Edelstein et al. (1998), which substituted EUVE DS data in place of the uncertain low energy ROSAT PSPC channels, has yielded a ($T_{\rm surface}$,$N_{\rm H}$) space differing markedly from earlier ROSAT results alone. Combining this new parameter space with independent model fits incorporating the B unpulsed upper limit suggests $T_{\rm surface} \geq 5.0 \times 10^5$ K (Golden 1998). It is possible to constrain R/d for B0656+14 in two ways – firstly by determining apparent expected radii using both column density and DM derived distances, and secondly by applying canonical or otherwise derived radius limits to yield optimum distance scales. $N_{\rm H}$ estimates towards PSR B0656+14, although by no means certain, suggest that the pulsar is $\sim$ 250-280 pc (Anderson et al. 1993, Edelstein et al. 1998), rather closer than the DM derived distance of 760 ± 190 pc. By manipulation of (3) with $T_{\rm surface} \geq 5.0 \times 10^5$ K and the range of G parameters determined from the unpulsed upper limit, the expected radial estimates for the $N_{\rm H}$ distances are $14.7 < R_\infty < 17.7$ km, and substantially greater in the case of the radio derived distance. We note that such radii estimates are *in excess* of the 14 km upper limit determined by Walter et al. (1997) for the old INS RXJ185635-3754. Alternatively, applying the ideal canonical $R_\infty \sim$ 13km, manipulation of (3) as above suggests that $205 \leq d \leq 227$ pc based upon the range of $E(B-V)$ estimates. This supports the conclusions of $PWC97$ although placing the pulsar somewhat in closer proximity than had been originally

thought. Indeed if one was to consider the proposed estimate of $R_\infty \sim 9.5^{+3.5}_{-2.0}$ km for Geminga as a working upper limit, this would place PSR B0656+14 at a distance of no less than d = 152^{+55}_{-32} for the suggested optimum colour index of $E(B-V)$ = 0.03 (PWC97)

4. Conclusions

The acquisition and analysis of optical photometric data on INS has been shown to provide an independent dataset from which constraints to the optimum thermal spectral energy distribution may be applied. We have attempted for the first time to apply the phase-resolved optical flux consistent with that expected *specifically* from the thermal component to the previous integrated analysis of the pulsars Geminga and PSR B0656+14. Despite being upper limits to the unpulsed optical flux in the B band, we find that in both cases, the resulting blackbody spectral distribution is constrained to the extent that we can set upper limits to the R/d parameter for both neutron stars. For the case of Geminga, with a known parallax derived distance of ~ 160 pc and using the lower $T_{\rm surface}$ limit, we suggest that $R_\infty \leq 9.5$ km for a $\sim$ blackbody source, and $R_\infty \leq 10.0$ km with the presence of a magnetized H atmosphere. Previous work using these unpulsed upper limits has suggested a $T_{\rm surface} \geq 5.0\times10^5$ K for the pulsar B0656+14 (Golden, 1998), and under the assumption of $R_\infty \sim$ 13km, places the pulsar at ~ 210 pc – in contrast to the DM derived distance of 760 pc. Assuming the neutron star has $R_\infty \leq 9.5$ km, then this limits the distance to ~ 160 pc. This suggests the possibility that the pulsar may be a viable candidate for a parallax measurement attempt using the HST.

Despite using upper limits to the unpulsed fluxes of these two INS, we have been successful in indicating how important such definitive measurements are in the rigorous derivation of a given neutron star's thermal parameters. In this way, we have independently provided limits to the radius of one, Geminga, and the distance of another, PSR B0656+14 and shown the promise to future studies this observational technique offers. This short report documenting these results is most timely, following on from a recent forum on the study of INS in this energy regime, at which the future importance of such high speed photometric studies was stressed (Romani 1998), and where a recent theoretical analysis based upon the discovery of RXJ185635-3754 has shown that neutron star radii should be ideally ≤ 10 km if one can hope to effectively constrain the EOS (An et al. 1998). That our results point to such a radius limit only emphasises the need for further high speed photometry of both pulsars, particularly Geminga, so as to provide definitive, rather than upper limit, fluxes of their unpulsed emission.

Acknowledgements. The authors acknowledge the financial support of *Enterprise Ireland*. The preliminary work was done by AG whilst a visiting RA at UC Berkeley and Stu Bowyer is thanked for his support during this time.

References

An, P., et al., 1998, AAS, 192, 82.07
Anderson, S.B., et al., 1993, ApJ, 414, 867
Bignami, G., et al., 1996, ApJ, 456, L111
Caraveo, P. A., et al., 1994, ApJ, 422, L87
Caraveo, P. A., et al., 1996, ApJ, 461, L91
Edelstein, J., et al., 1998, submitted to ApJ
Finley, J.P., et al., 1992, ApJ, 394, L21
Golden, A., 1998, $Ph.D\ Thesis$, NUI, Galway
Greiveldinger, U., et al., 1996, ApJ, 465, L35
Halpern, J.P. & Ruderman, M., 1993, ApJ, 415, 286
Halpern, J.P., 1997, ApJ, 477, 905
Lindblom, L., 1992, ApJ, 398, 569
Martin, C., et al., 1998, ApJ, 494, L211
Pavlov, G.G., et al., 1996, ApJ, 467, 370
Pavlov, G.G., et al., 1997, ApJ, 489, L75
Pavlov, G.G., et al., 1998, ApJ, 472, L33
Romani, R., 1987, ApJ, 313, 718
Romani, R., 1998, AAS, 192, 50.03
Savage, B.D., & Mathis, J.S., 1979, ARA&A, 17, 73
Shearer, A. et al., 1997, ApJ, 487, L181
Shearer, A. et al., 1998, A&A, 335, L21
Van Kerkwijk, M.H. et al., 1995, A&A, 303, 497
Wang, F.Y.-H. et al., 1998, ApJ, 498, 373
Walter, F.M & Matthews, L.M., 1997, Nature, 389, 358
Walter, F.M & An, P., 1998, AAS, 192, 50.04