Deep observations of PSR J0357+3205 with GTC†

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Summary

A middle-aged radio-quiet PSR J0357+3205 was detected in γ-rays with *Fermi* and later in X-rays with *Chandra* and *XMM-Newton*. It produces an unusual thermally-emitting pulsar wind nebula observed in X-rays. We present deep optical observations made with the Gran Telescopio Canarias (GTC) to search for optical counterparts of the pulsar and its nebula and to study their multiwavelength emission properties. The observations were performed in a direct imaging mode in the Sloan g' band. Archival X-ray data obtained with *Chandra* and *XMM-Newton* were also analysed. We haven't detected any source within the 2σ error circle of the X-ray pulsar position down to $28^{m}_{.}7$ (see Fig. 1). This implies that surprisingly the non-thermal power-law emission of the pulsar is much fainter than it would be expected from the X-ray data (see Fig. 2). At the same time the optical upper limit is in agreement with the upper limit on the temperature of the neutron star entire surface of 30 eV followed from the X-ray data (see Fig. 2). The surprising lack of the non-thermal emission in the optical band revealed with GTC hints that the thermal emission from the entire surface should dominate the PSR J0357+3205 emission in the UV range. This makes PSR J0357+3205 a promising target to study thermal properties of neutron stars in UV.

Perspective

Standard cooling theory which assumes the modified Urca processes as the main neutrino emission mechanism predicts T $\sim$ 35–50 eV for the stars of the PSR J0357+3205 age. The upper limit of 30 eV suggests that more efficient neutrino emission processes were operating inside the neutron star, or that the star is actually older than 0.5 Myr (see Fig. 3). If the surface temperatures of PSR J0357+3205 is actually less then 15 eV, than the minimal cooling scenario would be practically excluded and more effective cooling would be necessary. Future UV observations may allow us to detect thermal emission from the entire surface with temperature down to the 15 eV and find out whether the minimal cooling scenario actually operates or more effective cooling occurs.

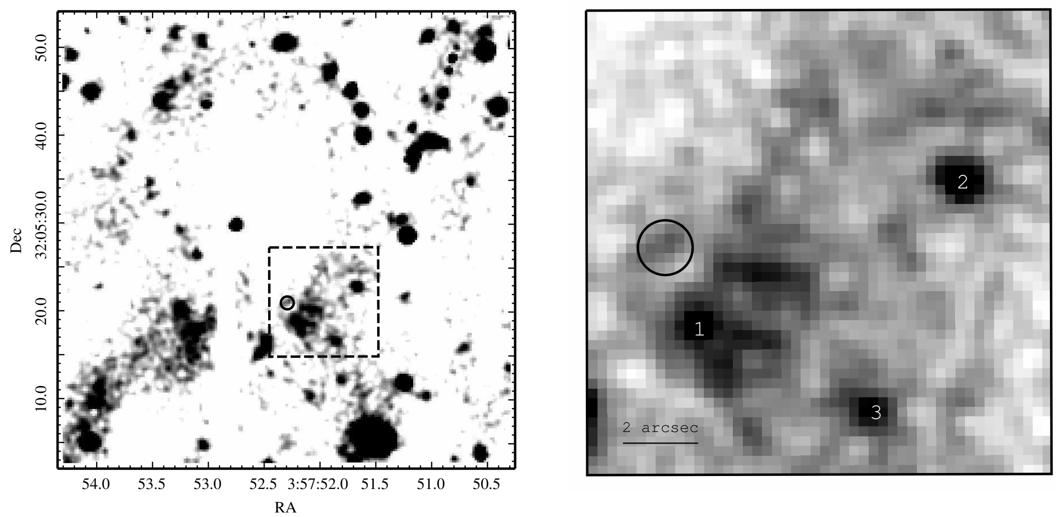

Figure 1: The $\sim 52'' \times 52''$ GTC/OSIRIS Sloan g' image fragment of the PSR J0357+3205 field (*left*) smoothed with a two pixel Gaussian kernel. The 2σ uncertainty circle is centred at the pulsar X-ray position for the optical observations epoch. The $\sim 12'' \times 12''$ dashed rectangle with the pulsar region is enlarged on the *right* panel.

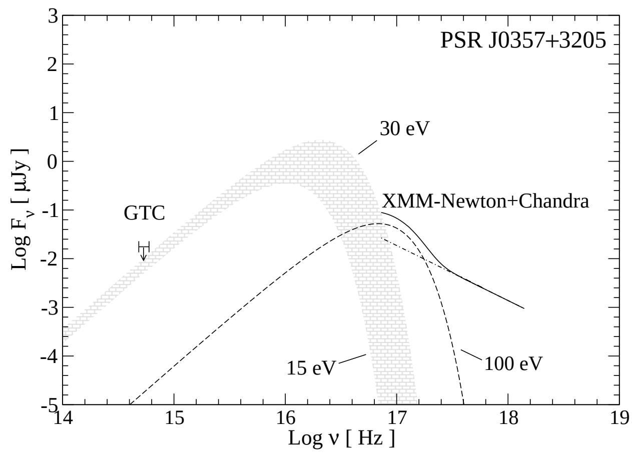

Figure 2: The best fit to the X-ray spectra of PSR J0357+3205 as seen by *Chandra* and *XMM-Newton* (solid line) assuming thermal emission of one hot spot (dashed line) plus non-thermal emission (dash-dotted line). The expected thermal emission from the entire surface of the neutron star is shown. Optical upper limit derived from the observations performed with GTC is also shown.

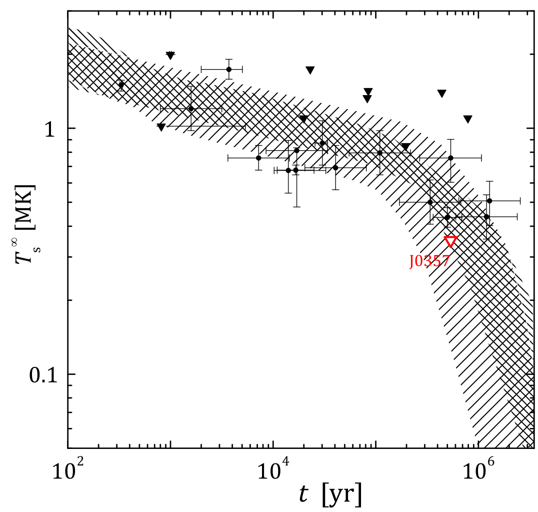

Figure 3: Measured NS entire surface temperatures T_s^∞ as seen by a distant observer (filled circles) and upper limits (filled triangles) in comparison with the cooling theory predictions (hatched regions). Dense hatched region correspond to the standard cooling theory, while sparse hatched region shows the minimal cooling theory predictions. Empty triangle shows the upper limit for PSR J0357+3205 followed from our X-ray spectral fitting.

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