INTEGRAL Observations of OAO1657-415: Gamma Ray Tomography of a B Supergiant

T. Bulik
CAMK, Bartycka 18, Warsaw, Poland
M. Denis and R. Marcinkowski
CBK, Bartycka 18a, Warsaw, Poland

INTEGRAL has been monitoring the eclipsing X-ray pulsar for over one year. We present the results of these observations. The 38 s pulsations have been detected. A careful analysis of the eclipse lightcurve allows to model the density profile in the outer atmosphere and stellar wind of the companion, a B supergiant. We also find that the models favor the inclination of the system close to the lower bound, i.e i=60-70 degrees.

1. INTRODUCTION

The accreting pulsar has been known since 1978 when it was discovered by the Copernicus satellite [4]. Soon after the discovery pulsations with the period of 37 seconds were identified [5]. The search for the companion ended successfully only three years ago, and was made possible by the Chandra localization [2]. The companion has been identified as a B supergiant. The distance is estimated to be $6.4 \pm 1.5\,$kpc. The spectrum is absorbed in soft X-rays, and has been modeled by a thermal spectrum with $kT \approx 15\,$keV and power law tail above 20 keV. There is a possible cyclotron line at 36 keV.

The INTEGRAL observatory allows to perform long term observations of the sources in the galactic plane. We present the analysis of INTEGRAL observations of the accreting pulsar OAO 1657-415 during the spring and fall of 2003. The total data acquisition time is 900 ks. The typical detection significance was 20-30 sigma. We have folded the data with the orbital period of 10.44 days found by BATSE [1], see Figure 2.

We note that the eclipse ingress and egress are not rapid but gradual. Since the X-ray source is practically point like this means that the eclipse probes the structure of the eclipsing supergiant. At his point one might assume that the pulsar emission region is of the size comparable with the red super giant companion. We have however two handles that can provide an estimate the size of the emission region in OAO1657-415. The first comes from the observed period of $\approx 37\,$s, which is quite long for a pulsar. Assuming that this is a rotational period leads to the estimate of the minimal average density of the star $\rho > 6 \times 10^6 \mathrm{g\,cm^{-3}}$, clearly pointing at a neutron star. A more direct estimate comes from the observed thermal spectrum with $kT \approx 15\,$keV, which given the estimate of the distance leads to the estimate of the emitting region size of $\approx 10\,$km. Therefore in order to explain the observed shape of the eclipse one has to consider the radiative transfer through the extended atmosphere of the companion.

2. MODEL OF THE ECLIPSE

In our model we assume that the atmosphere of the companion is totally ionized, and that the density profile of the atmosphere can be parameterized by an power law function:

$$\rho = \rho_0 \left(\frac{r}{r_0}\right)^{-\alpha}, \qquad (1)$$

where we chose $r_0 = 30\,R_\odot$ as our fiducial depth at which we estimate the density ρ_0. We solve the radiative transfer approximately, assuming that the opacity comes from the electron scattering only. In the ISGRI energy band between 20 and 40 keV this assumption is well justified. We calculate the optical depth by integrating the column density through the atmosphere of the star at each point of the orbit. The observed flux is them found by approximating the radiative transfer solution with

$$F = F_0 \exp\left(-\frac{\sigma_T}{m_p}\int \rho dx\right) \qquad (2)$$

where σ_T is the Thomson cross-section, m_p is the proton mass, and we integrate along the line of sight.

We have fitted the model to the data and obtained the following density profile of the supergiant companion:

$$\rho(r) = 10^{12.3\pm^{0.30}_{0.15}} \left(\frac{r}{30R_\odot}\right)^{-8.5\pm^{1.5}_{1.3}} \mathrm{cm}^{-3} \qquad (3)$$

At the same time these limits imply that the inclination of the system is close to the lower bound implied by the existence of the eclipses, however this conclusion depends on the physical model assumed above. The details of the fit are presented in [3].

3. RESULTS

We have modeled the shape of the eclipse in gamma-rays in OAO 1657-415. The main factor determining

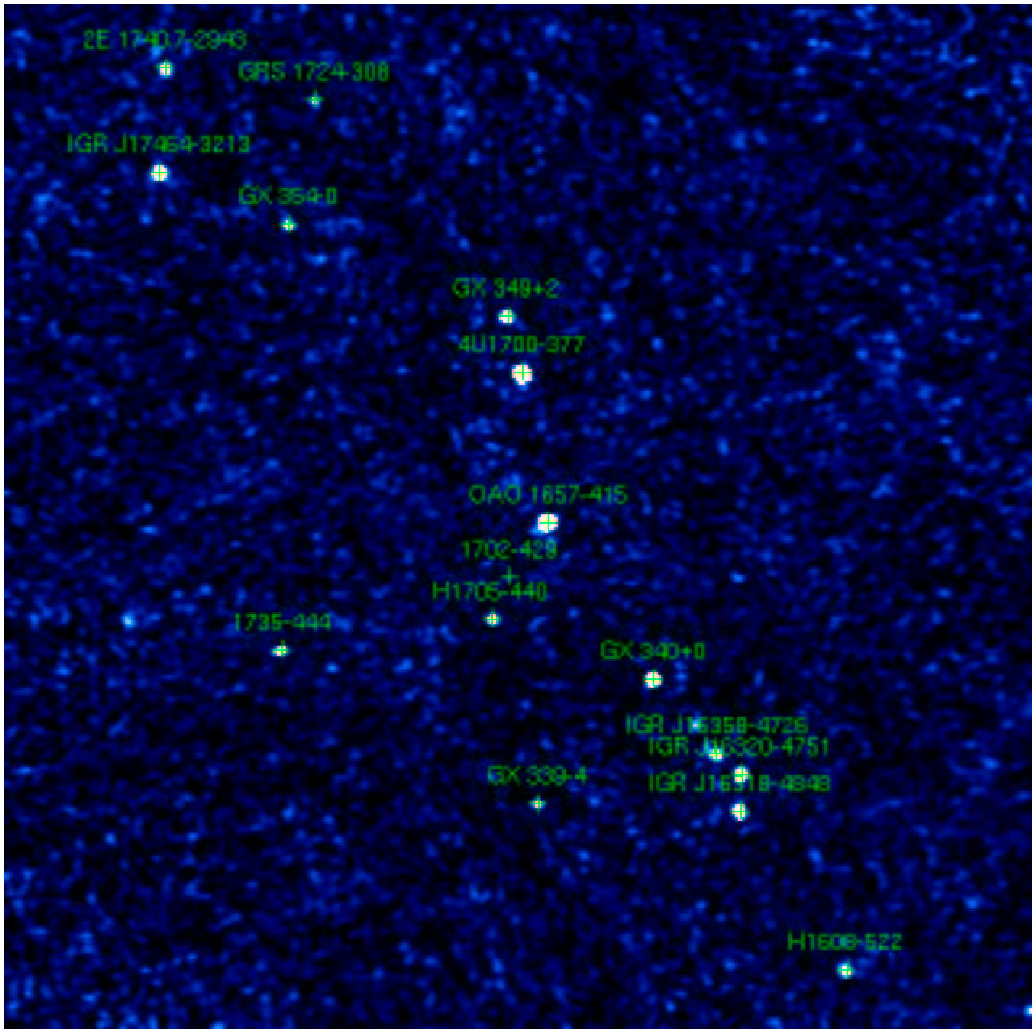

Figure 1: The skymap of the Galactic plane region centered on OAO

the shape of the eclipse is the transparency of the outer layers of the companion star to the gamma-ray radiation from the pulsar. Thus the long time monitoring of the eclipses is an important tool to probe the structure of the outer layers of the companion star.

The companion in the OAO 1657-415 system is a B supergiant and the accretion proceeds through the wind. The structure of the outer layers of the supergiant may in part reflect the wind acceleration process. If it is solely determined by the wind acceleration than the mass conservation leads to the estimate of the velocity profile as $v \approx r^{6.5}$.

Finally in Figure 2 we present the impact parameter as a function of the orbital phase (lower panel) along with the fitted lightcurve of the eclipse (top panel). The impact parameter b is defined as the projected distance between the neutron star and the center of the companion. A comparison of the two plots allows to estimate how deep the gamma-ray studies allow to probe the outer layers of the companion. The difference in the impact parameter corresponding to transition from the eclipse beginning to totality corresponds to the difference in the impact parameter of approximately $8R_{\odot}$. The radius of the B supergiant is estimated to be $\approx 35R_{\odot}$, thus probing the outer 25 percent of the size of the star.

Acknowledgments

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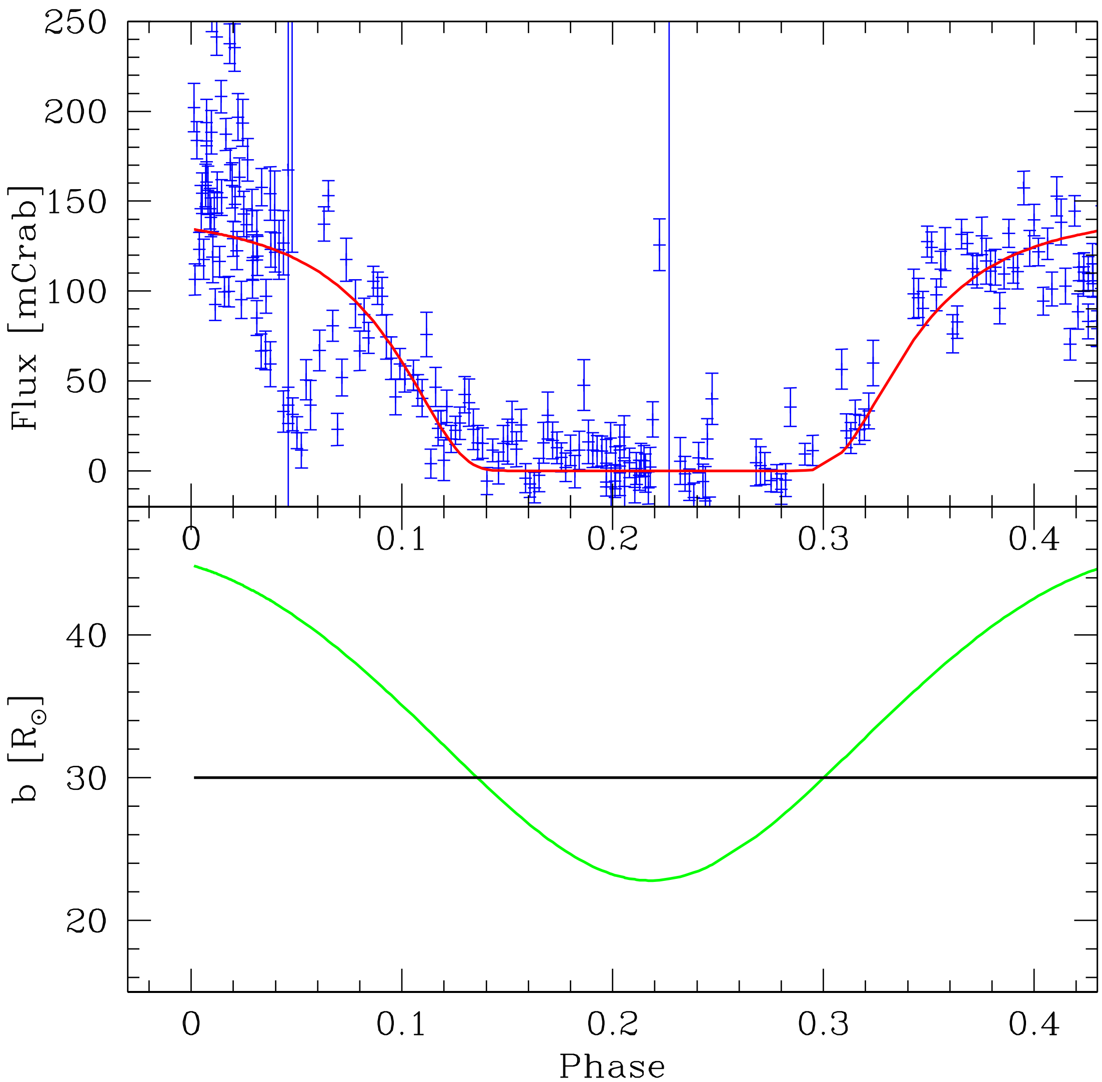

Figure 2: The top panel shows the data gathered from several pulsar orbits and folded with 10.44 day orbital period and the best fit model of the eclipse. The bottom panel shows the impact parameter b as a function of the orbital phase corresponding to the upper panel.

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