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Optical observations of PSR J2021+3651 with the GTC

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Abstract. We analyzed first optical observations of 17 kyr-old PSR J2021+3651 and its pulsar wind nebula obtained with the 10.4-m Gran Telescopio Canarias (GTC) telescope in the Sloan r′ band. In addition, we reanalyzed archival X-ray data obtained with Chandra. The pulsar and the nebula were not detected in the optical down to 27.20 and 24.85 magnitude 3σ limits, respectively. Using the optical and X-ray data we conclude that PSR J2021+3651, like the Vela pulsar, is a very inefficient nonthermal emitter in the optical and X-rays, while its gamma-ray efficiency is consistent with an average efficiency for all gamma-ray pulsars of similar ages.

1. Introduction
The pulsar PSR J2021+3651 with a period of 103.7 ms was discovered in the radio with the 305-m Arecibo telescope [¹]. With a characteristic age τc ≈ 17 kyr and a spin-down luminosity ˙E ≈ 3.4 × 10³⁶ erg s⁻¹, PSR J2021+3651 is one of the youngest and most energetic rotation-powered pulsars known. The canonical dipole magnetic field estimate from the pulsar period and its derivative is B ≈ 3.2 × 10¹² G. PSR J2021+3651 was identified in X-rays with Chandra [²]. The extended pulsar wind nebula (PWN) G75.2+0.1 was also revealed in this range. Its brightest internal part, within ~30″ of the pulsar, has a torus-like morphology with axial jets. This PWN was dubbed the Dragonfly Nebula owing to its specific spatial shape [³]. In addition, PSR J2021+3651 was detected in gamma-rays with the Fermi observatory [⁴]. The distance D to the pulsar is very uncertain and varies from 1 to 12 kpc, depending on the method applied to derive this parameter [³, ⁵].

Thus the pulsar was extensively studied in various spectral domains, but it has never been observed in the optical. In this work first optical observations of the PSR J2021+3651 are analyzed together with the archival X-ray data.
Figure 1. Left: $\sim 50'' \times 50''$ GTC/OSIRIS optical Sloan $r'$ image centered at the PSR J2021+3651 X-ray position. The closest to the pulsar source “A” is marked. Right: Chandra/ACIS-S X-ray image of the same field obtained by merging all available archival data. The pulsar position is marked by “+” in the X-ray image. Contours indicating the X-ray PWN boundary and the pulsar location are shown in both images. Colorbars show flux intensity in counts pixel$^{-1}$.

2. GTC data
PSR J2021+3651 was observed with the Optical System for Imaging and low-intermediate Resolution Integrated Spectroscopy (OSIRIS) at the GTC in Sloan $r'$ band in 2011 September 28 [5]. Observing conditions were photometric with a mean seeing of about 0'9. Sixteen images with exposures of 158 s each were obtained. Standard data reduction was performed with IRAF tools. For astrometric referencing we used the positions of stars from the USNO-B1 astrometric catalog. The resulting 1σ referencing uncertainty is $\approx 0.26''$. For photometric calibration we used the G158-100 Sloan standard observed at the same night as our target. The atmospheric extinction for the Sloan $r'$-band of 0.10$^{\pm}$0.01 mag airmass$^{-1}$ was taken from the OSIRIS user manual. The resulting magnitude zero-point for our data is $29.13^{\pm}0.02$.

3. Results
3.1. Optical counterpart
Figure 1 shows optical (left panel) and X-rays (right panel) images of the pulsar field. In X-rays the pulsar and PWN are clearly seen. The latter demonstrates a torus-like structure with two axial SW and NE jets [3]. Neither pulsar, nor PWN are detected in the optical. The nearest detected optical source “A” with $r' = 24.40^{\pm}0.04$ is located at about 4'8 or at $\approx 6\sigma$ from the pulsar X-ray position and thus is an unrelated object. We estimated optical flux upper limits for the pulsar and PWN using a standard method. For the pulsar, we used a mean background deviation within a circular aperture with 4 pixel (1'') radius centered at the pulsar position. We accounted for an aperture correction of $0''1$ obtained by us using bright background stars. The resulting 3σ upper limit on the pulsar flux density is $\leq 0.04 \mu$Jy ($r' \geq 27.20$). For the nebula, we used an elliptical aperture, centered at the pulsar, with semi-axes of 6.''2 and 10.''6 and a position angle of 137°, which encapsulates most of the X-ray PWN equatorial torus emission. The 3σ upper limit on the spatially integrated PWN flux density is $\leq 0.36 \mu$Jy ($r' \geq 24.85$). An average upper limit for the surface flux density is $\leq 1.74\times10^{-3} \mu$Jy arcsec$^{-2}$ ($r' \geq 30.63$ mag arcsec$^{-2}$).
3.2. X-ray data
For comparison of the optical upper limits with the X-ray spectra of the pulsar and PWN, we reanalyzed archival X-ray data, which were obtained with Chandra in the ACIS-S configuration in December 2006 and in February 2003 (obsIDs 3901, 7603, 8502) with 114 ks exposure in total. The pulsar equatorial coordinates RA=20:21:05.46 and Dec=36:51:04.52 were obtained in [3] and verified by us using the X-ray image in Figure 1. We extracted pulsar and PWN spectra using the CIAO 4.5 specextract task. For extraction of the PSR J2021+3651 spectrum, we used a circle region with a radius of 0′′.74, centered at the pulsar. For extraction of the PWN spectrum, we used the same elliptical region as used in the Section 3.1. We fitted all spectra in 0.3–10 keV range using XSPEC v.12.8.1 tools.

The pulsar and PWN spectra were fitted simultaneously, using the BB+PL, and NSMAX+PL spectral models for the pulsar, and the PL model for the PWN. The PL is a power law model describing nonthermal emission spectral component. It contains two unknown parameters, the normalization $K$ and the photon index $\Gamma$. The BB and NSMAX are the blackbody and magnetized hydrogen atmosphere models, respectively, describing the thermal emission from a neutron star (NS) surface. We also used the model of the photoelectric absorption PHABS in a product with each of these models to account for the interstellar absorption towards the pulsar. It is described by the hydrogen column density $N_H$, which was set as a global fit parameter. Standard interstellar medium abundances and absorption cross-sections were applied. In what follows, we do not indicate this multiplicative component explicitly for brevity. The simplest BB thermal emission model contains two unknown parameters – the temperature $T$ and the normalization $R^2/D^2$, where $R$ is the effective emitting area radius. The NSMAX model describes a more realistic case of the NS hydrogen atmosphere, hence its parametrization is more complicated. In addition to $T$ and normalization, it depends on the surface gravity via the gravitational redshift parameter $1+z=(1-2.952M_{NS}/R_{NS})^{-0.5}$, where $M_{NS}$ and $R_{NS}$ are the NS mass and circumferential radius in the units of Solar mass and km, respectively. We fixed $1+z=1.21$, which corresponds to reasonable NS parameters $M_{NS}=1.4M_\odot$ and $R_{NS}=13$ km. We also selected the specific NSMAX model with a surface magnetic field of $4\times10^{12}$ G, which is close to $B\approx3.2\times10^{12}$ G derived from PSR J2021+3651 spin-down measurements.

The PWN is bright enough and contaminates the spectrum of the pulsar. To model the contribution of the PWN to the spectrum extracted from the pulsar aperture, we added a second PL component of the PWN origin to the pulsar spectral model. The second PL photon index was tied with the PWN photon index, and its normalization was tied with the 5% fraction of the total PWN normalization. The latter value was estimated by Van Etten [3] and independently confirmed by us via modeling of Chandra/ACIS point spread function and analyzing the PWN spatial brightness profiles.

The described spectral fitting procedure can constrain only the $R/D$ ratio. To obtain $R$ and $D$ separately one needs to account for an additional information. We used the fact that $N_H$ increases with the distance to a Galactic source. To estimate the $N_H-D$ relation for the pulsar line of sight we employed the so-called “red-clump” stars method [6]. This relation was used to constrain $D$ from the inferred $N_H$ fit range, and then to constrain $R$ from $D$ and the thermal component normalization. The best spectral fit results for the pulsar are presented in Table 1. For the torus part of the Dragonfly the best-fit photon spectral index is $\Gamma=1.4^{+0.1}_{-0.1}$ and the unabsorbed flux in 2–10 keV range is Log $F_X = -12.2^{+0.4}_{-0.3}$ erg cm$^{-2}$ s$^{-1}$.

Both applied models equally well describe the pulsar spectrum, according to the reduced $\chi^2$ values about unity, see Table 1. The BB+PL model leads to a temperature of $155^{+14}_{-14}$ eV. It matches well to $T=160^{+20}_{-20}$ eV and $150^{+20}_{-20}$ eV obtained by Van Etten et al. [3] and Hessels et al. [2], respectively, who used the same spectral models, but fixed $N_H$ at a certain value. The distance of $1.8^{+1.4}_{-1.4}$ kpc is now mainly determined by $N_H$ and the $N_H-D$ relation [5]. As it is typical for pulsars, which X-ray spectral data can be equally well fitted by the blackbody
and NS atmosphere models, in former case R is apparently a factor of 10 smaller and T is a factor of 2.5 larger than those for the latter model. If the hydrogen atmosphere model is used, R = 12.0^{+9.5}_{-9.6} km implies that emission can come from the bulk of the NS surface with the effective surface temperature, redshifted for distant observer, T = 63^{+0.5}_{-0.3} eV, close to that of the Vela pulsar [7]. For the BB model, the thermal emission can be interpreted as coming from a small area with a radius of 1.3^{+1.5}_{-1.0} km, which is compatible with a canonical pulsar hot polar cap radius of ~ 0.6 km for a 100-ms pulsar [8].

4. Multiwavelength spectrum of the pulsar
The best-fit N_H values obtained from the X-ray spectral analysis suggest a total interstellar extinction towards the Dragonfly in the V band A_V ≈ 3.3 using the standard N_H – A_V relation [9]. This results in the extinction A_V ≈ 2.8 in the r′ band using a standard extinction law with R_V=3.1 [10]. Based on this, upper limits on the dereddened flux densities for the pulsar and PWN in the r′ band are about 0.57 µJy and 4.85 µJy, respectively. In Figure 2 we compare the derived pulsar upper limit with extrapolation of the unabsorbed X-ray spectrum as fitted by the BB+PL model. The solid line in Figure 2 shows the total best-fit model, including the contribution of PWN nonthermal photons to the spectrum extracted from the pulsar aperture. The dashed line shows solely the PL component of the pulsar. As expected, the PWN contribution is substantial only in the high-energy tail. For completeness we also show the extrapolation of the Fermi best-fit gamma-ray spectrum of the pulsar [4].

For all rotational powered pulsars detected in the optical and X-rays the nonthermal emission component dominates in the optical and usually shows a break between the optical and X-rays with significant spectral flattening in the optical [11, 12, 13, 14]. As seen in Figure 2, the pulsar optical flux upper limit does not exceed the extrapolation of the best-fit X-ray spectral model. This does not exclude the presence of the break for PSR J2021+3651, although the extrapolation is still rather uncertain and the optical limit is not deep enough. The same conclusions holds in the case when NSMAX+PL model is applied.

The optical upper limit for the PWN exceeds significantly the long wavelength extrapolation of its X-rays spectrum and does not constrain the PWN spectral parameters [5].

The pulsar’s 0.1–100 GeV γ-ray luminosity L_γ and efficiency η_γ = L_γ/E derived in the 2nd Fermi Pulsar Catalog [4] using the distance of 10 kpc from [2] appear to be unreasonably high [2]. In contrast, for the distance D=1.8^{+1.7}_{-1.4} kpc inferred from our analysis, Log L_γ = 35.3^{+0.6}_{-1.3} erg s^{-1} and Log η_γ = −1.2^{+0.6}_{-1.3} become consistent with the average values of the respective distributions.

Table 1. The best-fit parameters of the pulsar X-ray spectrum described by the BB+PL and NSMAX+PL models. The reduced χ^2 values in the last column obtained for 469 degrees of freedom. All errors correspond to 90% credible intervals.

| Model        | N_H 10^{21} cm^{-2} | Γ       | K 10^{-5} photons keV^{-1} cm^{-2} s^{-1} | T eV | R km | D kpc | χ^2  |
|--------------|---------------------|---------|----------------------------------------|------|------|-------|------|
| BB+PL        | 5.8^{+0.5}_{-0.5}   | 1.8^{+0.6}_{-0.6} | 1.0^{+1.0}_{-0.6}            | 155^{+14}_{-14} | 1.3^{+1.5}_{-1.0} | 1.8^{+1.5}_{-1.4} | 0.98 |
| NSMAX+PL     | 6.0^{+0.5}_{-0.5}   | 1.3^{+0.7}_{-0.8} | 0.5^{+0.7}_{-0.4}            | 63^{+9}_{-8} | 12.0^{+19.5}_{-9.6} | 1.8^{+1.7}_{-1.4} | 1.00 |
Figure 2. Unabsorbed spectrum of PSR J2021+3651. The solid line is the best-fit model for the Chandra X-ray spectrum which includes BB and PL pulsar spectral components. The best-fit model is extrapolated towards the optical. The GTC dereddened 3σ flux upper limit in the $r'$ band is shown by the bar with the arrow. Dash-dotted and dashed lines with light- and dark-gray regions are the BB and PL pulsar spectral and PWN components with their 90% uncertainties, respectively. The difference between the solid and dashed lines is clearly visible at the high-energy tail and reflects the PWN contribution. The gray dash-dotted line shows the extrapolation of the Fermi gamma-ray best-fit spectrum.

for γ-ray pulsars with similar $\dot{E}$ and/or characteristic ages [4].

The X-ray luminosity and efficiency are $\log L_X = 31.1^{+1.3}_{-2.0}$ erg s$^{-1}$ and $\log \eta_X = -5.4^{+1.3}_{-2.0}$, respectively, assuming the distance range derived in this work. For the 90% distance interval upper boundary of 3.5 kpc, upper limits on the optical luminosity and efficiency translated to the $V$ band are $\log L_V \leq 29.9$ erg s$^{-1}$ and $\log \eta_V \leq -6.7$, respectively. Both efficiencies are comparable to those of the Vela pulsar, which is known to be very inefficient nonthermal emitter in these ranges as compared to other younger and older pulsars. This makes PSR J2021+3651 a new member of the small sample of Vela-like pulsars forming a puzzling minimum in the efficiency-age dependence near a 10 kyr age [15].

5. Conclusions
We analyzed deepest up-to-date optical images of the PSR J2021+3651 field down to $r' = 27.2$. We did not detect the pulsar optical counterpart, but obtained important constrains on its optical-X-ray spectral energy distribution. From the X-ray spectral analysis and new constraints on the distance to a pulsar we estimated its luminosities and efficiencies in the optical, X-ray, and gamma-ray spectral domains. Based on that we concluded that PSR J2021+3651, like the Vela pulsar, is a very inefficient nonthermal emitter in the optical and X-rays, but its gamma-ray efficiency is consistent with an average efficiency for all pulsars of similar ages.

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