OPTICAL OBSERVATIONS OF PSR J2021+3651 IN THE DRAGONFLY NEBULA WITH THE GTC*

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1. introduction

The 104 ms pulsar J2021+3651 was discovered in the radio with the Arecibo telescope in a deep search for radio pulsations toward unidentified ASCA X-ray sources spatially coinciding with EGRET γ-ray objects (roberts et al. 2002). With the characteristic age τc ≈ 17 kyr and spin-down luminosity E ≈ 3.4 × 1037 erg s−1 this pulsar is among the youngest and most energetic rotation-powered pulsars known. The canonical dipole magnetic field estimated from the pulsar period and its derivative is B ≈ 3.2 × 1012 G. A tentative detection of γ-ray pulsations with the pulsar period in the EGRET data was reported by McLaughlin & cordes (2003). Later γ-ray observations with AGILE satellite (Halpern et al. 2008) and Fermi observatory (Abdo et al. 2009) firmly established a double-peaked pulse profile and a power-law (PL) spectrum with a photon index Γ ≈ 1.7 and cutoff energy of ∼ 2.9 GeV (Abdo et al. 2013). PSR J2021+3651 was also identified in X-rays with Chandra, and weak pulsations, also with the double-peaked profile, were detected at a 4σ significance (Hessels et al. 2004; Abdo et al. 2009). The pulsar X-ray spectrum contains thermal and non-thermal components from the surface and magnetosphere of a neutron star (NS), respectively (Van Etten et al. 2008). Chandra also revealed an extended pulsar wind nebula (PWN) G75.2+0.1 whose brightest internal part, within ∼ 30° of the pulsar, has a torus-like morphology with axial jets. By its specific spatial shape this PWN was dubbed the Dragonfly Nebula (Van Etten et al. 2008). A fainter diffuse emission is extended up to several arcminutes.

The PSR J2021+3651 position is projected on the Cygnus-X region, one of the richest known regions of star formation in the Galaxy. A bright extended TeV source MGRO J2019+37 was identified with the Milagro sky survey in this region with a 20 TeV flux of 80% of that of the Crab Nebula (Abdo et al. 2007). The source was suggested to be associated with the Dragonfly, which was recently confirmed by observations with the VERITAS observatory. VERITAS resolved the source into two objects (Aliu et al. 2014). The brightest one, VER J2019+368, has a hard spectrum resembling the spectrum of Vela X—a TeV PWN system powered by the Vela pulsar. VER J2019+368 coincides also with an extended region of non-thermal radio emission.

The most controversial parameter of PSR J2021+3651 is the γ-ray emission. The NE2001 model for the Galactic distribution of free electrons (Cordes & Lazio 2002) for the pulsar line of sight (l = 75°21, b = 0°11) and the dispersion measure DM ≈ 370 pc cm−3 yield a distance D ≈ 12 kpc (e.g., roberts et al. 2002). Comparing a hydrogen absorbing column density obtained from first X-ray observations and the total Galactic HI column density along the pulsar line of sight, Hessels et al. (2004) suggested D ≈ 10 kpc. Van Etten et al. (2008) performed similar analysis of subsequent deeper X-ray observations and found the distance of 3–4 kpc. The pulsar polarization rotation measure implies a minimal D ≈ 5 kpc (Abdo et al. 2009). adopting the latter value and assuming that PSR J2021+3651 was born near the center of VER J2019+368,
3. RESULTS

3.1. Searching for the Dragonfly and Pulsar Optical Counterparts

The 60″ × 60″ pulsar field fragment of the GTC/OSIRIS r’-band image, which contains the brightest part of the Dragonfly Nebula, is shown in the top-left panel of Figure 1. The image is smoothed with a Gaussian kernel with width σ = 2 pix. It is compared with the respective Chandra/ACIS-S 0.5–8 keV X-ray image (top-right panel of Figure 1), obtained by merging all the available archival data (112 ks effective exposure in total). The data were reprocessed with the CIAO v.4.6 chandra_repro tool with CALDB v.4.5.9. The X-ray image is binned by two ACIS pixels, smoothed with one-pixel Gaussian kernel, and shown in log-intensity scale. The X-ray PWN is comprised of a SW jet, NE counter-jet, and two arcs, which are oriented perpendicular to the jets. The arcs are believed to be associated with the PWN equatorial torus seen almost edge on (Hessels et al. 2004; Van Etten et al. 2008).

Contours in the X-ray image indicate the outer boundary of the torus-like PWN, where it blends with the background, and the region around the pulsar (marked by the cross). In the top-left panel of Figure 1 the X-ray contours are overlaid on the optical image. The vertical bold strip crossing the left side of the optical image is a bleed line from a bright over-saturated background star located outside the fragment. Two wave-shaped horizontal curves near the top side of the image are detector artifacts. Comparing the optical and X-ray images, we do not find any significant extended optical feature correlated with the X-ray morphology of the compact Dragonfly PWN. However, at an arcminute scale comparable to the faint diffuse X-ray emission extent, there are some background variations containing bright and dark regions seen in all individual exposures as well. Examination of Hα images of the field from the INT photometric survey of the northern sky (Barentsen et al. 2014) shows that these variations correlate with the Hα emission variations.

The immediate pulsar vicinity is enlarged in the bottom-left panel of Figure 1, where the r ≈ 2″ circle is centered at the pulsar X-ray position with R.A. = 20:21:05.46 and decl. = +36:51:04.8 (Hessels et al. 2004). It corresponds to the 3σ pulsar uncertainty, which accounts for the optical astrometric referencing and pulsar X-ray position uncertainties. No significant point-like objects are detected within the pulsar error circle. The closest reliably detected point-like source “a” with r = 24.40 ± 0.04 is located at about 4″8 or at ≈6σ from the pulsar X-ray position. More distant object “b” has a lower brightness of 25m01 ± 0″05 and is located at ≈9″4 or about 12σ from the pulsar. Because of their large offsets, both sources are unrelated to the pulsar.

Using our optical image we, therefore, can set only upper limits on the pulsar and the Dragonfly Nebula flux densities in the Sloan r’ band. For the pulsar, we used a mean background deviation within a circular aperture with a 4 pixel (≈1″) radius centered at the pulsar position. We accounted for an aperture correction of 0″1 derived using bright background stars. The resulting 3σ upper limit on the pulsar flux density is ≲0.04 μJy (r’ ≳ 27.2). For the nebula, we used an elliptical aperture with semi-axes of 6″2 and 10″6 and a position angle of 137°.

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Aliu et al. (2014) estimated a possible transverse velocity of the pulsar to be ≈840 km s⁻¹, which is about three times higher than the average for pulsar velocities (Hobbs et al. 2005). Finally, the distance can be as low as 1.5 kpc if the pulsar is located within the Cygnus-X region. This location is consistent with the empirical γ-ray “pseudo-distance” relation (e.g., Saz Parkinson et al. 2010) suggesting D ∼ 1 kpc.

By many multiwavelength properties PSR J2021+3651 and its PWN are similar to the Vela pulsar plus PWN system, but, in contrast to the Vela, this pulsar has never been studied in the optical. We report first deep optical observations of the PSR J2021+3651 field performed with the 10.4 m Gran Telescopio Canarias (GTC). We also address the issue of the distance discrepancies, using the Chandra archival X-ray data and red-clump (RC) stars as standard candles, and compare the optical results with the X-ray ones. The details of observations and data reduction are described in Section 2, our results are presented in Section 3 and are discussed in Section 4.

2. GTC DATA

2.1. Observations and Data Reduction

The pulsar field was imaged with the Optical System for Imaging and low-intermediate Resolution Integrated Spectroscopy (OSIRIS)8 in the Sloan r’ band at the GTC on 2011 September 28. 16 dithered 158 s exposures were obtained using the OSIRIS standard image scale of 0″254/pixel with the field of view of 7″8 × 7″8. The field was exposed on a mosaic of two CCDs, with the target source placed on CCD2. The observations were carried out during dark time, and the conditions were photometric, with seeing varying from 0″8 to 1″1.

Standard data reduction and analysis, including bias subtraction and flat-fielding, was performed with IRAF tools. To eliminate shifts between individual exposures, we collected a set of unsaturated stars in the field and aligned the images to the one with the best seeing using IRAF routines. The alignment uncertainty was ≲0.1 pixel. All exposures were then combined and yielded a final image with a mean seeing of 0″9, airmass of 1.8, and total integration time of ≈2.5 ks.

2.2. Astrometric Referencing and Photometric Calibration

For astrometric referencing, positions of 10 suitable astrometric standards from the USNO-B1.0 catalog⁹ were used. Their pixel coordinates were measured on the combined image with the IRAF task imcenter. The IRAF ccmap routine was applied to the astrometric transformation of the image. Formal rms uncertainties of the astrometric fit for the combined image were ∆R.A. ≤ 0″17 and ∆decl. ≤ 0″13. Accounting for the nominal catalog uncertainty of ≈0″2, this results in conservative estimates of 1σ referencing uncertainties of ≲0″26 for R.A. and ≲0″24 for decl.

The photometric calibration was carried out with G158-100 Sloan standard observed the same night as our target. The atmospheric extinction of 0.10 ± 0.01 mag airmass⁻¹ for the Sloan r’-band was taken from the OSIRIS user manual. The resulting magnitude zero-point for our r’ image is 29m13 ± 0m02.

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8 For instrument details see http://www.gtc.iac.es/instruments/osiris/.
9 http://www.nofs.navy.mil/data/fchpix/
centered at the pulsar, which encapsulates most of the X-ray PWN equatorial torus emission. The $3\sigma$ upper limit on the spatially integrated flux density of the PWN is $\lesssim 0.36\,\mu$Jy ($r' \gtrsim 24.8$).

### 3.2. Distance and Interstellar Extinction

It is possible to construct an extinction–distance relation for the direction toward the pulsar utilizing RC stars as standard candles, following a method described, for instance, in López-Corredoira et al. (2002) and Cabrera-Lavers et al. (2005). The method was used previously to constrain distances and extinctions for several sources. Some examples are the X-ray binary 4U 1608-52 (Güver et al. 2010), six anomalous X-ray pulsars (Durant & van Kerkwijk 2006), and two $\gamma$-ray pulsars (Danilenko et al. 2012, 2013).

In the top panel of Figure 2, we show $K$ versus $J - K$ band color–magnitude diagram for stars from the 2MASS All-Sky Point Source Catalog located within 0\degree of the pulsar position. The RC branch, as well as main-sequence (MS) and asymptotic-giant (AGB) branches, are indicated. We divided the diagram into several magnitude bins, and in each bin we fitted $J - K$ color distribution with a mixture of two Gaussians corresponding to the MS and RC branches. The AGB stars were eliminated by omitting all points located right of a boundary starting at $J - K = 1.7$ for small magnitudes and ending at $2.5$ for large ones. The derived $J - K$ colors of RC stars with their uncertainties were then transformed into distances and interstellar extinctions $A_V$, using relations from

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11 See [http://irsa.ipac.caltech.edu/applications/DataTag/](http://irsa.ipac.caltech.edu/applications/DataTag/); DataTag = ADS/IRSA.Gator#2014/0814/100517_7624.
Figure 2. Top: $K$ vs. $J - K$ diagram for the stars from the 2MASS All-Sky Point Source Catalog located within 0.3 of the pulsar position ($J = 75^\circ 22$, $b = 0^\circ 11$). The main-sequence (MS), red-clump (RC), and asymptotic-giant (AGB) branches are indicated. Solid line shows a smoothed spline approximation to the RC stars mean colors; dashed segments are its extrapolations to higher and lower $K$ magnitudes. Light-shaded region bounded by dotted-dashed lines contains 95% ($2\sigma$) of RC stars. Bottom: empirical $N_H$–distance relation for the PSR J2021+3651 direction derived using the RC stars colors from the diagram at the top panel. Bars are $1\sigma$ uncertainties. The solid line and gray filled region are smoothing spline approximations to the data points and their uncertainties, respectively. They are linearly extrapolated to small and large distances (dashed lines).

Rieke & Lebofsky (1985), assuming the absolute magnitude and the intrinsic color of the RC stars to be $M_K = -1.62 \pm 0.03$, and $(J - K)_0 = 0.68 \pm 0.07$, respectively (see the above-cited papers for details). Extinctions were transformed to hydrogen absorbing column densities $N_H$ using a standard empirical relation $N_H = A_V \times (1.79 \pm 0.03) \times 10^{21} \text{cm}^{-2}$ (Predehl & Schmitt 1995).

The resulting $N_H$–distance dependence is shown in the bottom panel of Figure 2. $N_H$ increases with the distance reaching a limit of $(15 \pm 4) \times 10^{21} \text{cm}^{-2}$ at distances $\gtrsim 5$ kpc. Within uncertainties this limit is consistent with the total Galactic $N_H$ in the pulsar direction of $\approx 12 \times 10^{21}$ and $\approx 9.7 \times 10^{21} \text{cm}^{-2}$, estimated from the HI maps provided by Dickey & Lockman (1990) and Kalberla et al. (2005), respectively. Corresponding $A_V = 8.4 \pm 2.2$ is also compatible with the entire Galactic extinction estimate of $\approx 11^{\circ}0$ (Schlafly & Finkbeiner 2011), although the respective extinction map is considered as not reliable at $b \lesssim 5^\circ$.

3.3. X-ray Spectral Analysis

We reanalyzed the archival Chandra data in light of the $N_H$–distance relation. We extracted the pulsar spectra from all three Chandra/ACIS-S sets using an aperture with a radius of $0.774$ centered at the pulsar position applying the CIAO v. 4.6 specextract tool. We also extracted the PWN spectrum from an elliptical region with semi-axes of $6.2$ and $10.6$ and a position angle of $137^\circ$, that encloses most of the PWN equatorial torus. The circle aperture of a $2''$ radius around the pulsar was excluded from this region. Backgrounds were taken from regions free of any sources on the ACIS-S3 chip, where the Dragonfly was exposed in all three Chandra data sets with live times of 19, 59, and 43 ks. Total numbers of source counts are $\approx 1270$ for the pulsar and $\approx 5250$ for the PWN.

To evaluate likelihoods, we used the $\chi^2$ statistics. To model the pulsar spectrum, we applied an absorbed sum of the PL and thermal components. Any single component did not describe the data. For the thermal component, we tried blackbody (BB) and magnetic NS hydrogen atmosphere models NSA (Pavlov et al. 1995) and NSMAX (Ho et al. 2008). For the interstellar absorption, we used the XSPEC photoelectric absorption phabs model with default cross-sections bmod (Balucinska-Church & McCammon 1992) and abundances angr (Anders & Grevesse 1989).

To model the contribution of the PWN to the spectrum extracted from the pulsar aperture, we added second PL to the pulsar spectral model and fitted the PSR and PWN spectra simultaneously in the 0.3–10 keV spectral range. The second PL component photon index was tied with the PWN photon index, and $N_H$ was set as a global parameter. Doing this, we also took into account the ratio of the PWN flux within the pulsar aperture to the total PWN flux of $\approx 0.05$, as it was estimated by Van Etten et al. (2008) and independently confirmed by us via modeling of Chandra/ACIS PSF.

The $N_H$–distance relation and its uncertainty were approximated by smoothing splines, shown by the line and gray filled region in the bottom panel of Figure 2. This relation was then used as a Bayesian prior information for the subsequent spectral fitting procedure (see, e.g., Gelman et al. 2003, for details). Technically, we assumed that for each distance the $N_H$ value follows a Gaussian distribution with the mean and $\sigma$ taken from the approximations. We then run Markov chain Monte Carlo (MCMC) using the Goodman–Weare algorithm implemented as a python package emcee by Foreman-Mackey et al. (2013). For each model we kept 1000 steps after initial burn-in, which is large enough considering that typical autocorrelation time (see, e.g., Goodman & Weare 2010) was of order of several tens (50–90) of iterations. As 100 MCMC walkers (Goodman & Weare 2010) was used, we obtained 100,000 samples in total.

Posterior median values of spectral parameters with 90% credible intervals for the BB+PL and NSMAX+PL models are presented in Table 1. The goodness-of-fit test ($\chi^2$ values are in Table 1) shows that both models are equally consistent with the data. We present fit results for only one of hydrogen atmosphere models, NSMAX 1260, which corresponds to the...
The surface magnetic field $B = 4 \times 10^{12} \text{ G}$ (Ho et al. 2008). The thermal component can be equally well fitted by NSA or by any other model from the NSMAX set; the resulting parameters do not depend appreciably on the choice of specific atmosphere model. We prefer more modern NSMAX models because they account for the partial ionization in stellar atmospheres, especially important at low temperatures (as in our case), while the NSA models were constructed for fully ionized NS atmospheres.

Our results are generally consistent with those presented by Hessels et al. (2004) and Van Etten et al. (2008). However, in contrast to Van Etten et al. (2008), we did not fix $N_H$ at a best-fit value obtained from a separate analysis of the PWN spectrum. Nevertheless, the resulting $N_H$ is defined mainly by the PWN spectrum, and consistent with the one obtained by Van Etten et al. (2008) within uncertainties. Thereby it weakly depends on a particular model used to describe the pulsar spectrum and on a particular $N_H$--$D$ relation. The distance $D = 1.8^{+1.4}_{-0.6} \text{kpc}^{12}$ is now mainly determined by $N_H$ and the adopted $N_H$--$D$ relation. In this approach, only two parameters are defined by the thermal component: the radius $R$ and the effective temperature $T$ of the emitting area. Importantly, we were able to infer the absolute value of the radius $R$, not only the $R/D$ ratio as it would have been without accounting for the $N_H$--$D$ relation. As it is typical for pulsars where X-ray spectral data can be equally well fitted by the BB and NS atmosphere models (e.g., Pavlov et al. 2001; Kirichenko et al. 2014), for the BB model $R$ is a factor of 10 smaller and $T$ is a factor of 2.5 larger than those for the hydrogen atmosphere model. For the latter, $R = 12^{+2}_{-10} \text{ km}$ implies that emission can come from the bulk of the NS surface with the effective surface temperature, redshifted for a distant observer, $T = 63^{+6}_{-3} \text{ eV}$, close to that of the Vela pulsar (Pavlov et al. 2001). For the BB model, $R = 1.3^{+1.0}_{-0.5} \text{ km}$, which is compatible with a canonical pulsar hot polar cap radius of $\sim 0.6 \text{ km}$ for a $100 \text{ ms}$ pulsar (Sturrock 1971).

### 3.4. Multiwavelength Spectra of the Pulsar and PWN

The best-fit $N_H$ values obtained from the X-ray spectral analysis suggest a total interstellar extinction toward the Dragonfly $A_V \approx 3.3$ in the $V$ band, which results in the extinction $A_V \approx 2.8$ in the $r'$ band using a standard extinction law with $R_V = 3.1$ (Cardelli et al. 1989). Based on this, upper limits on the dereddened flux densities for the pulsar and PWN in the $r'$ band are about 0.57 and 4.85 $\mu$Jy, respectively. In Figure 3 we compare these limits with unabsorbed X-ray spectra of the pulsar (top panel) and PWN (bottom panel), fitted by BB+PL and PL models, respectively. For the PWN, the optical and X-ray data were obtained from the same spatial region enclosing its X-ray equatorial torus emission (see Sections 3.1, 3.3, and Figure 1). The solid line in the top panel of Figure 3 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 seen, the PWN contribution is substantial only in the high-energy tail.

As seen from Figure 3, the pulsar optical flux upper limit does not exceed the extrapolation of the best-fit X-ray spectral model to the optical. This is typical for rotation powered pulsars detected in the optical and X-rays (Shibanov et al. 2006; Mignani et al. 2010; Danilenko et al. 2011; Durant et al. 2011). For all of them, the nonthermal component dominates in the optical. However, this component usually shows a break between the optical and X-rays with a significant spectral flattening in the optical. Our data do not exclude the presence of such a break for PSR J2021+3651, although the extrapolation of the X-ray PL component is still rather uncertain and the optical limit is not deep enough. The NSMAX+PL model, which equally well fits the X-ray data, does not change these conclusions.

All torus-like PWNe, which have been detected in both spectral domains, also show spectral flattening in the optical in comparison with X-rays (e.g., Zharkov et al. 2013). However, for the Dragonfly the situation is currently even less certain than for its pulsar. The nebula optical flux upper limit overshoots the low-energy extrapolation of its X-ray spectrum (bottom panel of Figure 3), and the presence of the break in the spectrum of this PWN remains an open question.

The dereddened upper limits were obtained using the $A_V = N_H$ relation of Predehl & Schmitt (1995). There exist other empirical relations of that kind. For instance, Güver & Özel (2009) give $N_H = A_V \times (2.21 \pm 0.09) \times 10^{21} \text{ cm}^{-2}$, also consistent with the results of Gorenstein (1975). Using this relation instead, we get smaller $A_V \approx 2.7$ and hence dereddened upper limits smaller by a factor of 1.6, which does not change general conclusions of this Section.

### Notes

- BB+PL and NSMAX+PL Models are for the Pulsar Spectrum. While the PWN is Described by the PL Model. $N_H$ is the absorbing column density. The temperatures $T$ and emitting area radii $R$ for the BB and NSMAX spectral components are given as measured by a distant observer. For the NSMAX component, the gravitation redshift $1 + z = (1 - 2.952 M/R_{\text{NS}})^{-0.5}$, where $M$ and $R_{\text{NS}}$ are the NS mass and circumferential radius in the Solar mass and km units, respectively, is fixed at 1.21. This corresponds to NS with $M = 1.4$ and $R_{\text{NS}} = 13$ km. $K_{\text{psr,pwn}}$ and $\Gamma_{\text{psr,pwn}}$ are PL normalizations and photon spectral indexes for the pulsar (psr) and PWN (pwn), respectively. All errors correspond to 90% credible intervals derived via MCMC.

- Non-thermal pulsar fluxes in 2--10 keV range are log $F_{\text{ps}}^{\text{X}} = -13.5^{+2.8}_{-0.3}$, $-13.4^{+1.2}_{-1.1}$ (erg cm$^{-2}$ s$^{-1}$), for BB+PL and NSMAX+PL models, respectively. PWN flux in the same range is log $F_{\text{ps}}^{\text{X}} = -12.2^{+0.1}_{-0.1}$ (erg cm$^{-2}$ s$^{-1}$) for both models.

### Table 1

| Model     | $N_H$ ($10^{21} \text{ cm}^{-2}$) | $\Gamma_{\text{psr}}$ | $K_{\text{psr}}$ ($10^{-5} \text{ photons keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$) | $T$ (eV) | $R$ (km) | $D$ (kpc) | $\Gamma_{\text{pwn}}$ | $K_{\text{pwn}}$ ($10^{-5} \text{ photons keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$) | $\chi^2$ (dof) |
|-----------|---------------------------------|------------------------|-------------------------------------------------|---------|---------|---------|----------------|---------------------------------|-------------|
| BB+PL     | $5.8^{+0.5}_{-0.5}$             | $1.8^{+0.6}_{-0.6}$    | $1.0^{+1.0}_{-0.6}$                              | $155^{+14}_{-14}$ | $1.3^{+1.5}_{-1.0}$ | $1.8^{+1.3}_{-1.4}$ | $1.4^{+0.1}_{-0.1}$ | $9.7^{+1.2}_{-0.9}$                  | 459(469)    |
| NSMAX+PL  | $6.0^{+0.5}_{-0.5}$             | $1.3^{+0.7}_{-0.8}$    | $0.5^{+0.7}_{-0.4}$                              | $63^{+8}_{-9}$  | $12.0^{+2.8}_{-1.6}$ | $1.8^{+1.4}_{-1.7}$ | $1.4^{+0.1}_{-0.1}$ | $10.0^{+1.0}_{-0.9}$                  | 472(469)    |

12 Here and below we discuss the largest $D$ range from Table 1.
hour exposure in \( r' \) at good seeing conditions, although observations at longer wavelengths, less affected by the interstellar absorption, would be preferable. Such observations would also be useful to better constrain the optical-X-ray spectral properties of the PWN.

Our \( N_{\text{H}} \)-distance relation, constructed using the RC star method and compiled with the X-ray spectral analysis, supports previous suggestions that the pulsar is likely to be substantially closer to us than it is inferred from DM and the NE2001 model of the Galactic distribution of free electrons. Our estimate \( D = 1.8^{+1.7}_{-1.4} \) kpc is compatible, within uncertainties, with the 3–4 kpc range suggested by Van Etten et al. (2008). However, our allowed distance range is shifted to lower distances. It suggests the association of the pulsar with the Cygnus-X region, located within 2 kpc from the Sun, and is consistent with the \( \gamma \)-ray “pseudo-distance” of \( \sim 1 \) kpc provided by the \textit{Fermi} data. The reduced distance we found makes feasible parallax and pulsar proper motion measurements with very long baseline interferometry. A possible source of systematic errors in our distance determination method originates from ambiguity in \( A_{\nu} - N_{\text{H}} \) relations, as stated above. Reprocessing the analysis of Sections 3.2 and 3.3 using the relation of Güver & Özel (2009), we obtain an even smaller distance of \( 1.3^{+1.5}_{-1.1} \) kpc.

Comparing the DM of \( 370 \) pc cm\(^{-3} \), or electron column density \( N_e \approx 1.4 \times 10^{21} \) cm\(^{-2} \), with \( N_{\text{H}} \) of \( 6 \times 10^{21} \) cm\(^{-2} \) leads to an average ionization ratio of 19% along the pulsar line of sight which is not too much larger than the 10% ionization found on average (e.g., He et al. 2013, Figure 1). On the other hand, the NE2001 electron density model in the pulsar direction gives much smaller \( N_e = 0.7^{+1.2}_{-0.5} \times 10^{20} \) cm\(^{-2} \) for distance range of \( D = 1.8^{+1.7}_{-1.4} \) kpc. There exist several indications that the NE2001 model strongly underestimates \( N_e \) in the vicinity of the PSR J2021+3651 direction (Camilo et al. 2009, 2012; Arumugasamy et al. 2014). For instance, there is another pulsar J2022+3842 at only \( 18\) from PSR J2021+3651 with very high DM = 429 pc cm\(^{-3} \), for which NE2001 model gives obviously overestimated distance \( D > 50 \) kpc (Arumugasamy et al. 2014). This may imply that there are dense clouds in the Cygnus-X region, which are not taken into account in the NE2001 model (Roberts et al. 2002).

As for the X-ray thermal emission component of PSR J2021+3651, we cannot state definitely whether the thermal emission comes from a hot polar cap or the bulk of the NS surface. This depends on which, BB or a hydrogen atmosphere, model is applied to describe the thermal emission. The phase-resolved spectroscopy would be useful to distinguish between the two possibilities. We note, however, that if the thermal emission originates from the entire surface of the star (the case of the atmospheric model), PSR J2021+3651 has a rather small surface temperature for its age. According to the NS cooling theories, such a small temperature cannot be explained by a standard cooling scenario, but it can be reached if the effects of superfluidity in the stellar interiors are invoked. This is possible, for instance, if the powerful direct Urca process of neutrino emission operates in the star but is suppressed by superfluidity (Yakovlev & Pethick 2004). In another interpretation the direct Urca process is not allowed, but the cooling is enhanced due to the specific process of the neutrino emission accompanying the Cooper pair formation in the neutron triplet superfluid. This is the essence of the so-called minimal cooling scenario (Gusakov et al. 2004; Page et al. 2004, 2009).

### Figure 3
Top: 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 and the PWN contribution to the spectral extraction aperture (see text for details). The best-fit model is extrapolated toward the optical. The GTC dereddened 3\( r' \) flux upper limit in the 3\( r' \) band is shown by the bar with the arrow. Dashed-dotted and dashed lines with light- and dark-gray regions are the BB and PL pulsar spectral 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. Bottom: the solid line and gray region are the best-fit PL model of the X-ray spectrum of the PWN equatorial torus region with its 90% uncertainties, respectively. The difference between the solid and dotted lines with light- and dark-gray regions are the BB and PL pulsar spectral components with their 90% uncertainties, respectively. The difference between the solid and dotted lines with light- and dark-gray regions is also shown. The error-bar crosses in each panel are the unfolded Chandra data.

### 4. DISCUSSION

Our rather deep, down to \( r' \approx 27.2 \), GTC optical imaging of the Dragonfly Nebula field allowed us to set upper limits on the optical flux densities of PSR J2021+3651 and its PWN. The non-detection of this energetic system can be attributed to high interstellar extinction toward the object, which is roughly about 3\( m \) in the \( r' \) band. Considering the data for other pulsars detected in the optical and X-rays, we conclude that 1–2 magnitude deeper optical observations are necessary to detect this pulsar and to reveal the expected spectral break between the optical and X-rays. This is, in principle, feasible with 8–10 m ground-based telescopes, such as the GTC, using a few
The pulsar’s 0.1–100 GeV γ-ray luminosity \( L_\gamma \approx 5.9 \times 10^{36} \text{erg s}^{-1} \) and efficiency \( \eta_\gamma = L_\gamma / \dot{E} \approx 1.8 \), derived in the 2nd Fermi Pulsar Catalog (Abdo et al. 2013) using the distance of 10 kpc from Hessels et al. (2004) appear to be unreasonably high, and place the pulsar at the highest end of \( L_\gamma \) and \( \eta_\gamma \) distributions of γ-ray pulsars. In contrast, for the distance \( D = 1.8^{+1.7}_{-1.4} \) kpc inferred from our analysis, \( \log L_\gamma = 35.3^{+0.6}_{-1.3} \) (erg s\(^{-1}\)) and \( \log \eta_\gamma = -1.2^{+0.6}_{-1.3} \) become consistent with the average values of the respective distributions for γ-ray pulsars with similar \( \dot{E} \) and/or characteristic age (cf., Figures 9 and 10 of Abdo et al. 2013).

The pulsar’s unabsorbed nonthermal X-ray flux in 2–10 keV range, derived from the X-ray spectral fit, is \( \log F_X = -13.5^{+0.8}_{-0.8} \) (erg cm\(^{-2}\) s\(^{-1}\)). The respective X-ray luminosity and efficiency are \( \log L_X = 31.1^{+1.3}_{-1.1} \) (erg s\(^{-1}\)) and \( \log \eta_X = -5.4^{+1.3}_{-1.2} \), assuming the distance range derived in this work.

For the 90\% distance upper limit \( D = 3.5 \) kpc, upper limits on the optical luminosity and efficiency in the \( V \) band, assuming a flat spectrum, are \( \log L_{\text{Opt}} \lesssim 29.9 \) (erg s\(^{-1}\)) and \( \log \eta_{\text{Opt}} \lesssim -6.7 \), respectively. In Figure 4 we compare the obtained X-ray and optical efficiencies and luminosities with the data for other pulsars observed in both ranges (Danilenko et al. 2013). According to Figure 4, we can conclude that PSR J2021+3651, like the Vela pulsar, is inefficient in these ranges. We thus obtain a new member of the small sample of Vela-like pulsars forming a puzzling minimum in the optical and X-ray efficiency dependences on age at a characteristic age of \( \sim 10 \) kyr noticed previously by Zharikov et al. (2006). No such minimum is visible in the respective γ-ray dependence (Abdo et al. 2013). Together with strong glitches and high polarization in the radio (Hessels et al. 2004), a bright NS thermal emission component in X-rays, a double arc X-ray PWN with jets (Van Etten et al. 2008), γ-ray activity (Abdo et al. 2009), and association with a TeV source (Aliu et al. 2014), this makes the Dragonfly pulsar and PWN remarkably similar to the Vela pulsar and its PWN.

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**Facilities:** GTC, CXO.

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**Figure 4.** X-ray and optical luminosities, \( L_X \) and \( L_{\text{Opt}} \), and respective efficiencies, \( \eta_X \) and \( \eta_{\text{Opt}} \), for pulsars of different characteristic age \( \tau \) studied in both spectral domains. The data are adopted from Danilenko et al. (2013). Different pulsars are marked by different symbols. The PSR J2021+3651 data, derived in this work, are included (marked by cross).
