Optical spectroscopy of the Guitar nebula

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Summary

Guitar is an extended Hα nebula which has a specific guitar shape produced by the radio pulsar PSR B2224+65 moving with a supersonic velocity in the ISM. For the first time the nebula was discovered in Hα imaging with the 5-m Hale telescope at Palomar (Cordes, Romani & Lundgren, 1993) and later imaged twice with the *HST* (Chatterjee & Cordes, 2002, 2004). This is a typical example of the pulsar bow-shock nebulae. To our knowledge, so far only eight Hα bow-shock nebula have been imaged around neutron stars. Only three of them, the Guitar Nebula (Cordes Romani & Lundgren, 1993), a fainter nebula around the binary millisecond pulsar PSR B1957+20 (Kulkarni & Hester, 1988; Aldcroft Romani & Cordes, 1992) and recently reported Hα nebula around the γ-ray pulsar PSR J1741 — 2054 (Romani et al., 2010) have been partially studied spectroscopically in the optical range. Spectra of all three bow-shocks reveal weakness of forbidden emission lines relative to hydrogen lines Hα and Hβ and therefore these bow-shocks are non-radiative and similar to Balmer-dominated shocks (BDSs) in young supernova remnants whose theory and observations are reviewed recently by Heng (2010). We present results of the optical spectroscopy of the Guitar nebula carried out with the 3.6-m Telescopio Nazionale Galileo (TNG). The long-slit spectroscopy with a medium ($\sim$1.25 Å) spectral resolution in a narrow spectral range (6232–6888 Å) has allowed us to resolve the Hα emission line profile and to estimate the magnitude and direction of the pulsar velocity and the distance to the pulsar independently. Our data show that the velocity and the distance are likely to be about 200 km s^{-1} and 250 pc, respectively, or about five times smaller than it was previously estimated ($\sim$1000 km s^{-1} and $\sim$1000 pc), based mainly on the proper motion and dispersion measure observations of the nebula and the pulsar.

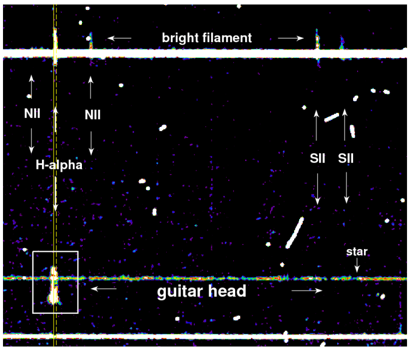
Observations

We acquired medium resolution long-slit spectra with the DOLORES instrument installed at the Nasmyth B focus of the TNG 3.58-m reflector at La Palma Observatory. The key parameters of the observation and the slit position are presented in the Table and Figure below.

Table: Summary of the TNG observations

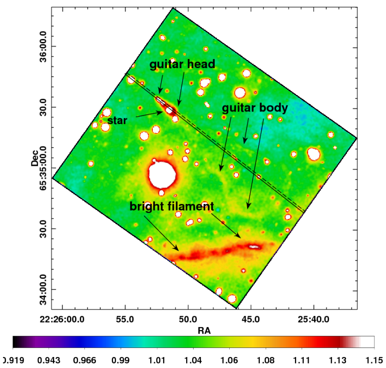
Date	2008 August 4–5 UT
Spectral resolution	$\sim$1.25 Å (57 km s^{-1})
Spectral coverage	6232–6888 Å
Dispersion	0.32 Å/px
Average seeing	$\sim1''.5$
Integration	14400 s (4 h)
Slit width	$1''$

2D spectra

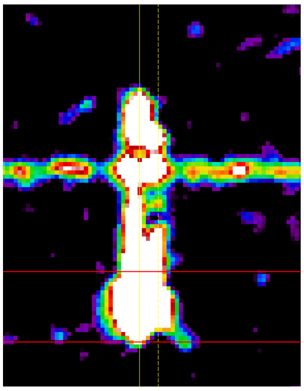


The left-hand panel shows 2D spectrum of the Guitar. The spatial axis goes along columns and the dispersion axis goes along lines. We have subtracted all background or sky lines. A yellow bar shows the Hα line without subtraction. The width of the yellow bar is equal to the FWHM of the instrument's profile or spectral resolution. The Hα line of the Guitar head is within a white box. The Hα line of the Guitar head is appreciably wider than the yellow bar and apparently shifted towards shorter wavelengths relative to the latter while the bright-filament's Hα coincides pretty well with the yellow bar both in width and position. There aren't any signatures of the forbidden SII and NII lines in the guitar-head's part of this 2D spectrum while SII and NII are clearly seen in the filament's part. On the left-hand panel below we enlarge the region inside the white box to present Hα line in more details and show the aperture used to extract the 1D spectrum shown on the right-hand panel below.

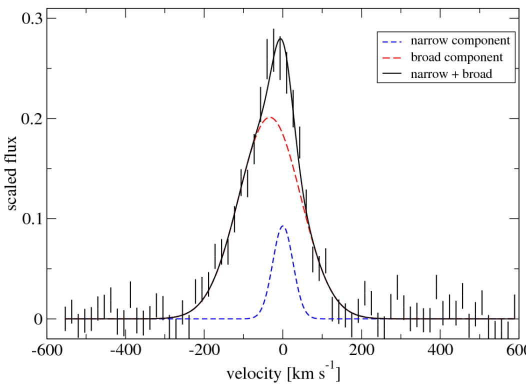
Slit position



Aperture



Hα line profile



Fitting two-component profile of the Balmer-dominated-shock's radiation model to the Hα line

According to the model of the Balmer-dominated shocks (Heng, 2010), hydrogen lines consist of two, narrow ($\sim$ 10 km s^{-1}) and broad ($\sim$ 1000 km s^{-1}), components. A broad component is produced by downstream protons, whose temperature is given by

$$T = \frac{3\mu m_p v_s^2}{16}, \qquad (1)$$

here, $\mu \approx (1 + 4\chi_{He})/(2 + 3\chi_{He})$ is the mean molecular weight, m_p – the proton mass and v_s is the shock velocity. We assume $\mu = 0.61$, which is a typical value for our Galaxy. The full width at half maximum (FWHM) of the broad component is given by

$$FWHM = \sqrt{\frac{3\mu \ln 2}{2}}\, v_s. \qquad (2)$$

The velocity offset between the centroids of narrow and broad components depend on the shock velocity and the aspect angle of the shock, ϑ_i,

$$\Delta = \frac{3}{4} v_s \cos \vartheta_i. \qquad (3)$$

We may approximately consider v_s to be the pulsar velocity and ϑ_i to be the inclination angle, i.e the angle between the pulsar velocity and the line of sight. Using equations (2) and (3) we may estimate the pulsar velocity and the inclination angle. Then using these estimates and results of the proper motion measurements (Harrison, Lyne & Anderson, 1993) we may also estimate a distance to the pulsar. We have fitted two Gaussians to the observed guitar-head's Hα line profile. Best-fitting results are shown in the right-hand Table. Obtained estimates of the distance to the pulsar and its velocity are about five times smaller than it was previously assumed based on the proper motion and dispersion measure observations of the nebula and the pulsar (Cordes, Romani & Lundgren, 1993; Chatterjee & Cordes, 2002, 2004). It is also necessary to note an unusual low value of the ratio of narrow to broad component's intensities, I_n/I_b (see Heng, 2010).

Table: Best-fitting parameters.

χ^2 per dof	1.15
Best-fitting parameters of the profile:	
FWHM, km s^{-1}	185 ± 10
I_n/I_b	0.15 ± 0.04
Δ, km s^{-1}	-33 ± 7
Estimates of the parameters of the pulsar:	
Shock velocity, V_s, km s^{-1}	232 ± 10
Velocity of the pulsar, V_p, km s^{-1}	$\simeq 232$
Distance to the pulsar, D, pc	$\simeq 259$
Inclination angle	$\simeq 169^{\circ}$

Conclusion

It seems that we have detected spreading of the Hα line produced by hot neutral hydrogen atoms accelerated on the Balmer-dominated non-radiative bow-shock. The corresponding FWHM indicates that distance to the PSR B2224+65 and its velocity of are about five times smaller than it was previously estimated (see, e.g., Cordes, Romani & Lundgren, 1993; Chatterjee & Cordes, 2002, 2004).

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