Probing the age of 3C58 via multiwavelength observations

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Introduction

The Northern sky plerionic nebula 3C58, is the most firm candidate to be the remnant of the supernova explosion occurred in 1181 CE[1]. It is very similar to the Crab Nebula in age, distance and elliptical morphology of the compact nebula but on the other hand it is much bigger and less luminous than the Crab.

Our knowledge on 3C58 comprises of a filled-centre radio nebula of about 9'×5' with a flat spectral index of 0.1 and upper limits on the infrared flux. Optical filaments are observed, but no synchrotron emission in optical has been detected yet. X-rays show a non-thermal nebula of the same size as its radio counterpart in the 0.1 to 1.0 keV interval, whereas the X-ray size reduces with increasing energy. In the centre, a pulsar (PSRJ0205) was discovered with a measured spin period of 65 ms.

Several authors have suggested that 3C58 cannot be the remnant of the SN1181, as some of its observed properties such as the expansion rate or the velocity of the optical filaments are inconsistent with the large size of the nebula. A few months ago, a new radio measurement[2] with a flow velocity of 630 ± 70 km/s considers again the historical association very unlikely.

Aim

Aiming at giving a prediction for the inverse Compton γ-ray fluxes, we model 3C58 to explain the synchrotron nebular emission in terms of photon index versus distance from the pulsar, the synchrotron surface brightness and termination energy dependent size. Other models, such as KC84[3] have already failed in reproducing the photon index vs radius measured by both XMM-Newton[4] and Chandra[5] Observatories.

The age of the remnant enters into the time it takes the wind to propagate from the pulsar to the outer edge of the nebula, influencing the flow velocity of the wind and hence the field distribution. The latter again determines the amount of energetic particles in the remnant, which in turn determines the VHE γ-ray flux. Assuming different ages for the SNR we want to study the potential constraints from γ-ray observations into the age of this system

Model Description

The rotational energy lost by the pulsar is converted into relativistic electrons and fields ar or before the shock radius (r_S) is reached:

$$\dot{E} = I\Omega\dot{\Omega} = eff \int_0^\infty Q(E)EdE$$

A general model for particle injection at the shock radius is assumed:

$$Q(E) = K(E/E_0)^{-g1}, E < E_0$$
$$K(E/E_0)^{-g2}, E_0 < E < E_{\max}$$

where g1 and g2 are the electron spectral indices for radio and X-rays respectively and E_0 reflects the energy to which the bulk of the population have been accelerated.

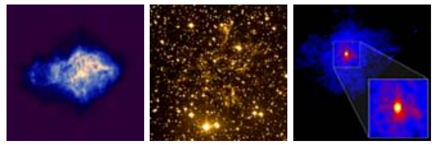
In this model the nebular flow velocity v(r) is described by the principle of magnetic flux conservation:

$$\nabla \times (\vec{v} \times \vec{B}) = 0 \longrightarrow \frac{v(r)B(r)r}{1+\gamma^2} = const$$

Using a trial B(r) and assuming a boundary condition at r_S, v = c/√3 , v(r) is calculated in radial steps of 1" starting at the shock. The electrons are transported radially, suffering adiabatic and synchrotron losses in each step:

$$-\frac{dE}{dt} = \frac{E}{3}\nabla \cdot v_\perp + 2.37\times10^{-3} B_\perp^2 E^2$$

The synchrotron and IC spectra are also calculated radially, in order to compute the line-of-sight integrals to compare surface brightness against observations, allowing us to derive fundamental wind parameters using a best-fit analysis



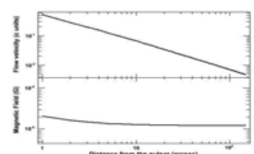
Three images of 3C58 corresponding to radio, optical and X-rays, respectively. The radio nebula, which is a recent image made using the NRAO Very Large Array Telescope, shows a beautiful filamentary structure. In the same field of view, the optical image taken from 1.3m McGraw-Hill contains only filaments. The last picture is the synchrotron nebula in X-rays obtained with Chandra, which shows a similar torus-jet strucure as seen for the Crab Nebula.

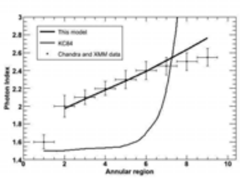
Model Prediction

X-rays

The adopted parameters for the modeling are the ones in Table 1. The resultant mean magnetic field is between 10 and 12 μG, which is well below the equipartition value of 80 μ G. An argument in favour of this weak field comes the fact that the high energy electrons emitting X-rays survive to the edge of the nebula. The field strength is almost constant, which explains why the flow velocity drops with 1/r.

The nebular flow velocity (∝1/r) and the magnetic field strenght (∝ const) as a function of the distance from the pulsar as dericed for this model.





Variation of the photon spectral index with radius in 3C58. The data points represent the averaged photon indices from measurements of XMM and Chandra. The thick solid line is the predicted variation in our model for the total PWN, whereas the one based on KC84 is indicated by the thin solid line.

PARAMETER	VALUE
Pulsar Period	65 ms
Spindown power	2.7×10^{37} erg/s
Distance	3.2 kpc
g1	1.2
g2	2.4
E0	0.6 ergs
Shock radius	0.5''-1''

Table 1. Adopted parameters

Our model predicts a break between 0.5 and 1 keV, in the spectral energy distribution (SED) of synchrotron and IC, which is consistent with an uncooled electron spectral index g2<3. The differences obtained with the ASCA spectrum are due the different calibration between instruments.

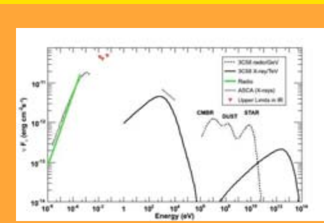
Radio

The radio flux is underestimated by two orders of magnitud with our model . This is solved by considering that the radio electrons were produced when the pulsar was relatively young, adding a relic component at present.

PROBLEM: The total amount of energy in electrons injected to the system is estimated to be 6×10^{48} ergs. This is 6 times larger than the total energy dumped by the pulsar into 3C58 over the last 824 years.

$$E_{dump} = \frac{1}{2} I(\Omega_0 - \Omega) = 8.1\times10^{47} erg$$

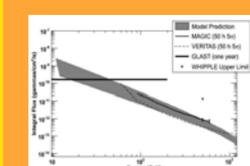
assuming the pulsar to have a braking index n = 3.



Spectral Energy Distribution (SED) of synchrotron and IC emission of the radio (dashed line) and X-ray (solid line) emitting electrons in 3C58. The IC from the radio component show three peaks corresponding to the scattering of radio electrons on the 2.7 K CMBR, 25K dust and the starlight photon field from left to right , haveing used 0.26, 0.2 and 0.15 eV /cm³ respectively in this model, that is a dominant CMBR component. GLAST may be able to detect line-like features and measure the relative energy densities of the different components.

γ-rays

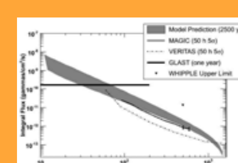
In 3C58, like all other PWNe, it is expected that electrons radiating X-ray photons will also scatter the 2.7 CMBR into the VHE regime. We also include the IC scattering on the 25 K dust and starlight components. The predicted integral spectrum at Earth is at the threshold of the Northern hemisphere Cherenkov telescopes VERITAS and MAGIC



The predicted integral flux for γ-rays compared to the sensitivities of the Cherenkov telescopes in the northern hemisphere, when the hisotrical association is conidered

To account for the possibility that the true age is about 2500 years (suggested by Chevalier) we found a new set of wind parameters fitting the observational X-ray data. The resulting predictions are well above the MAGIC sensitivity, so that VHE observations should give us an indication if the system is really much older than the historical age

The same prediction when consideriing an age of the SNR of 2500 years



Conclusion

- A Kennel & Coroniti solution for Crab-like PWNe does not support the observations of 3C58. Assuming reasonable boundary conditions we found the pulsar wind nebula parameters which reproduce the observed surface brightness and steepening of the X-ray spectrum with radius as measured by the XMM-Newton and Chandra.

- We predict the potential constraints coming from γ-ray observations. According to this model , telescopes such as VERITAS or MAGIC can shed light on the age problem.

References

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