Determination of the energy and kick velocity of Crab Nebula pulsar from the distribution morphology of the remnant

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Abstract

The Plerion nebula is characterized by its pulsar that fills the center of the supernova remnant with radio and X-ray frequencies. In our galaxy there are nine naked plerionic systems known, of which the Crab Nebula is the best-known example. It has been studied this instance in order to investigate how the pulsar energy affect on the distribution and evolution of the remnant as well as study the pulsar kick velocity and its influence on the remnant. From the obtained results it's found that, the pulsar of the Crab Nebula injects about $(2-3)x\ 10^{47}$ erg of energy to the remnant, although this energy is small compared to the supernova explosion energy which is about 10^{51} erg but still plays a significant role in the distribution and the morphology as well as the dynamical expansion of the remnant. However, most of this energy is concentrate in the direction of the pulsar rotational dipole axis which makes the remnant expanding in this direction further than other regions and consequently has more density. Moreover, it's found that the pulsar kick velocity which is in order ≈ 110 km.s^{-1} also adds an expansion energy to the remnant in the direction of the kick (North West direction) added to its initial energy and due to this kick the pulsar will be shifts to the opposite direction of the kick the South East direction, which cause the pulsar to leave its birth position and finally leave the remnant itself.

Key words
Pulsar, planetary wind nebula, kicks velocity.

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حساب طاقة وسرعة الركلة لنابض سديم العقرب باعتماد التوزيع الجغرافي للبقايا

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الخلاصة

يتميز سديم العقرب بنابضه الذي يعد مصدراً للترددات الراديوية والسينية في مركز بقايا المستعرة العظمى. في مجرتنا هناك تسعة انظمة فريدة و معروفة لهذا النوع من السدم ويعتبر سديم العقرب من افضل الامثلة عليها. تمت دراسة هذا النظام لمعرفة كيفية تاثير طاقة النابض و سرعة ركلته على توزيع وتطور البقايا. وجد من النتائج المحصلة أن نابض سديم العقرب يضخ تقريبا $(2-3)x\ 10^{47}$ أرك من الطاقة الى البقايا، و بالرغم من ان هذه الطاقة صغيرة مقارنةً بطاقة انفجار المستعرة العظمى والتي تساوي 10^{51} أرك الا انها لا تزال تلعب دوراً هاماً في التوزيع والشكل اضافة الى التوسع الديناميكي للبقايا.ووجد ان معظم هذه الطاقة تكون مركزة في اتجاه المحور الدوراني لثنائي قطب النابض مما يؤدي الى توسع البقايا في هذا الاتجاه اكثر من الاتجاهات الاخرى وتبعاً لذلك سوف تكون كثافتها اكبر من كثافة باقي مناطق البقايا. بالاضافة الى ذلك، لقد وجد أن سرعة الركلة للنابض والتي هي ≈ 110 كم/ثا تعد مصدراً اضافياً للطاقة التوسعية للبقايا الواقعة في اتجاه الركلة (الاتجاة الشمالي الغربي) تضاف الى طاقتها الابتدائية وبسبب هذه الركلة فان النابض سوف يتحرك الى الاتجاه المعاكس للضربة (الاتجاة الجنوبي الشرقي) مما يجعله يغادر موقع ولادته وبالتالي مغادرته البقايا نفسها.

Introduction

The best example to study the plerion remnant is the Crab nebula. Crab nebula is a young Galactic supernova remnant that exploded at 1054 A.D in the constellation of Pursues in the arm of the Milky Way galaxy at a distance of 2 kpc [1] (α=05^h 34^m 1.94^s and δ= +22^o 00′ 52.2" [2]) and its cataloged as M1, as the first object on Charles Messier's famous 18th century list of objects which are not comets. The remnant has an elliptical expansion morphology of debris left over from the violent death of an especially massive star (likely an O or B type star with ten or more solar masses) and it's characterize by its fast rotating radio pulsar (PSR 0531+21) that located near the center of the supernova explosion. From its discovery in 1968, by Comella et al. using radio wavelengths observations [3], till now PSR 0531+21 had obtain a big attention from the astronomers since it was the first pulsar to be associated with a supernova explosion providing the first evidence that clearly paved the way for the interpretation of pulsars as neutron stars.

Moreover beside its pulsar, Crab nebula has some other unique characteristics, perhaps most importantly its cavity explosion. HI observations showed that the Crab Nebula exists inside a relatively empty bubble that has a radius of about 90 pc which would affect the remnant in two ways: First, the lack of surrounding interstellar medium would affect the overall evolution of the remnant because the blastwave from the explosion would not be encountering a significant amount of gas to slow the propagation of the shock front [4]. This means that the blast wave would have to travel significantly farther than in the typical Type II SN explosion and takes more time in order to form a reverse shock, as a result it takes long time in order to enters to the Sedov-Tyler phase since the swept mass will need long time to be equal to the ejected mass which is the condition of the remnant to enters in the second stage from its evolution.

Second, the low density of the surrounding gas is not high enough to give rise to detectable circumstellar emission when interacting with the ejecta; neither X-ray nor radio searches have indicated any evidence of circumstellar interaction between fast ejecta and ambient gas [5]. All that made Crab nebula and its pulsar among the most studied objects in the sky from radio to gamma ray frequencies.

Pulsars and pulsar wind nebula

A core collapse supernova is always characterized by its neutron star that left after the supernova explosion. Typical neutron star is highly magnetized (of the order of 10^{12} G) [4] and has a rapid rotation (typically 1-10ms) [6] that resulted from the conservation of the angular momentum and the freeze-out of the magnetic field inside a mass ranging from 0.1$M_\odot$ to 2$M_\odot$ that concentrated within a radius of 10-20 km. However, as is usual in rotating bodies of magnetic fields (such as the Earth) , the magnetic axis and rotation axis do not coincide, causing the former to process about the latter at frequencies typically about 10–100 times a second [6], as a result a beam of highly energetic particles (electromagnetic radiation) will be emitted along the magnetic dipole axis. If this beam happens to sweep past our line of sight, a periodic signal of energetic radiation will be measured from the neutron star, which then is called a pulsar, as an example is the pulsar of the Crab nebula which is one of very few pulsars to be identified optically with a very short pulse period of only 0.033 s [7].

However, pulsars are known to convert a significant fraction of its spin-down energy into a powerful wind which consists of electromagnetic energy and highly relativistic particles. The kinetic energy of this wind is converted into relativistically hot plasma (electrons/positrons accelerated to ultra-relativistic energies) at a termination shock. This hot plasma is believed to be the source of the observed synchrotron emission which produces the bulk of the emission from the nebula, seen from radio waves through to soft gamma rays [8].

The interaction between this wind and the neutron star's environment gives a rise to a complex structure known as Pulsar Wind Nebula (PWN). In such cases the dynamics of the central region of the SNR will be dominate with the continuous injection of energetic particles with a relativistic pulsar wind driven by the spin-down energy of the pulsar itself, as a result the pulsar wind will be terminated by a strong MHD shock that drives a PWN in the interior of the SNR [9].

As the pressure of the ejecta surrounding the PWN is low, the expansion of the PWN bubble which inflated by the wind particles thermalized and re-accelerated at the termination shock will be supersonically, faster than the surrounding stellar ejecta, which results in a shock propagating into the ejecta and in the same direction for the forward SNR shock [10]. Moreover, at the very earliest times (t < 100 years), the magnetic field of the PWN will be very strong since the energy input for the neutron star ($E^{\cdot}$) is larger than the adiabatic losses resulting from the PWN's expansion causing the internal energy of the PWN to rise which makes the synchrotron luminosity of the PWN approach $E^{\cdot}$ [11]. After that (t ≤1000 years) the magnetic field will decrease rapidly since the synchrotron losses dominate over adiabatic and inverse Compton losses resulting in a steep decline in the PWN's synchrotron luminosity, while the energy of the PWN and its pressure increases due to the continued injection of particles into the PWN. This behavior will continue until the PWN collides with the reverse shock from the supernova explosion which happened after 4500 years from the supernova explosion [11].

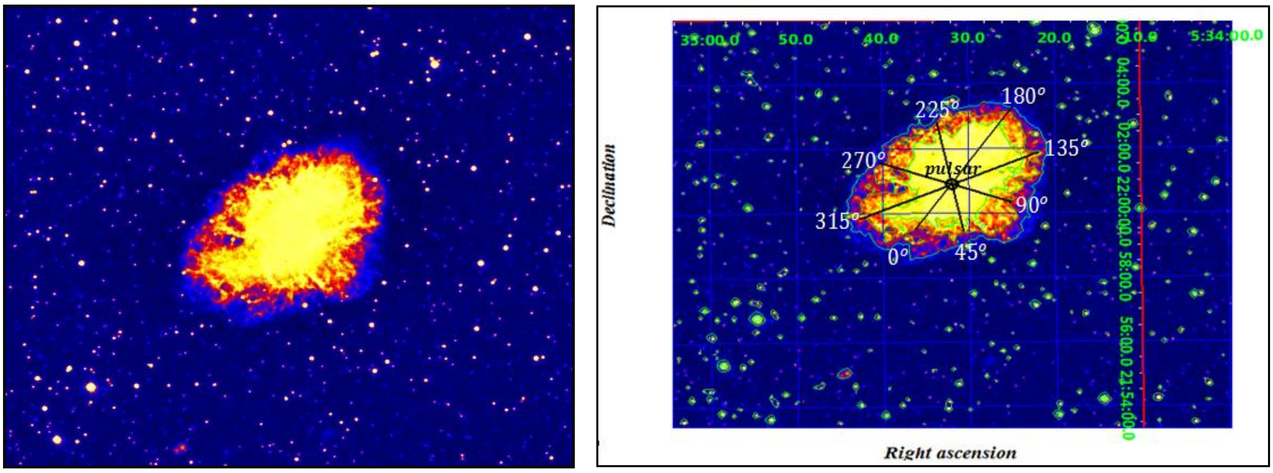
When the reverse shock of the SNR arrives at the boundaries of the inflating bubble, the PWN is crushed, contract and re-expand inside the SNR (eventually stripping the neutron star of its PWN) leading to Rayleigh-Taylor instabilities which sequentially leads to mixing of the thermal and non-thermal material in addition to strengthening the magnetic field within the PWN [12]. As a result of that, a two PWNe phase inside the SNR will rise a "relic" PWN containing the particles injected into the neutron star at earlier times, and a "new" PWN composed of particles injected by the neutron star after it leaves the "relic" PWN [11]. Furthermore, due to the inhomogeneities of the interstellar medium that surrounds the SNR, the SNR will be in different evolutionary phases at the time of crush so the reverse shock will reach different sides of the PWN at different times. Due to the high kick velocity of the pulsar and a density gradient in the surrounding of the SNR, the PWN will be displaced from the pulsar leaving behind a remnant nebula which is still detectable in radio. But in the very rare case where the SNR and PWN are symmetric, the PWN will not be displaced from the pulsar, and the oscillating behavior of the nebula will eventually wear off and settle into expansion once more [12].

This oscillating behavior will continue on a time scale of a few thousand years. Then after the oscillations have faded the pulsar will steadily increase its nebula around its current position. Ultimately the expansion of the PWN becomes subsonic and at some point it will reach pressure equilibrium with its surroundings and its expansion will end [13].

In this paper we will only focus on the energy of the pulsar that is injected into the plerion remnant and added to its kinetic energy during the free expansion stage and study how this energy and the discrepancy of the medium density affect the dynamical structure of the remnant and its expansion.

Calculations, results and discussions

In this paper the image of Crab nebula has been taken from SAO-DSS [14] and locate the pulsar position on it ($\alpha=05^h\ 34^m\ 31.97^s$ and $\delta= +22^o\ 00'\ 52.1''$ [15]) using SAO Image DS9 software. After that the image has been divided into eight regions with constant angle as shown in Fig. 1. When the dynamical parameters of each region were calculated using the Counting Pixels Method (CPM) (see reference [16]) it has been noticed that, there is a large discrepancy between the region in the North West (NW), South East (SE) and the other regions as shown in Table 1.



(a) (b)

Fig. 1: a: Image of Crab nebula taken from SAO-DSS [14]
b: image (a) after locate the pulsar position on it and divided into eight regions with constant angle.

Table 1: The dynamical parameters of the remnant of Crab Nebula at different angles.

Angel	No. of Pixel	Radius (pc)	Velocity (km. s^{-1})
0^o	67	1.3	1348
45^o	55	1.0666	1106
90^o	61	1.183	1227
135^o	85	1.648	1709
180^o	76	1.474	1528
225^o	80	1.551	1608
270^o	74	1.435	1488
315^o	82	1.588	1644

From the results of Table 1 its shown that, the radius as well as the velocity at angle 135^o & 315^o (region in the NW and SE) were larger than the other regions and this explained by that, since these region are located in the same direction of the pulsar magnetic dipole axis they will experience a continuous injection of energy from the pulsar itself which make their kinetic energy to increase constantly and as a result their dynamical expansion will increase too.

The difference in the velocity between the regions at angle 135 ^{o} & 315^o and the average velocity of other regions had been taken (which is ≈300 km. s^{-1}) in order to calculate the pulsar energy but first the mass of the remnant (m) must be calculated from the following equation:

$$m = \frac{4}{3}\,\pi\,\rho\,R^3 \qquad (1)$$

where:

ρ is the mass density of the surrounding interstellar medium, R is the radius of the remnant.

After that the equation of the kinetic energy has been applied which is given by:

$$E_k = \frac{1}{2}\,m\,v^2 \qquad (2)$$

By applying Eqs. (1) & (2) the injected energy of the pulsar to the remnant have been obtained which is about (2-3 x 10^{47} erg) this result has a good agreement with the result that had obtained by Bietenholz et.al 2004 using the Crab pulsar spins down luminosity, $E^{\cdot} = \frac{\partial E}{\partial t} = 5 \text{ x } 10^{38}$ ergs of rotational energy per second [17].

On the other hand when the pulsar position (α=05^h 34^m 31.97^s and δ= +22^o 00′ 52.1") located on the image of Fig. 1 it was noticed that, the pulsar did not locate in the center of the remnant but it's near to it (slightly shifted to the SE). This is explained by the kick velocity of the pulsar itself which is usually at this stage (free expansion stage) much smaller than the velocity of the remnant expansion which makes the pulsar has no time to move far away from its birth site. This velocity is raised from a strong asymmetry resulted during the supernova explosion: when the core is pushed slightly to one side off center from the star with a high pressure it will cause a large energy to be released, making the core to push back the other way which in turn adds greater pressure on the other side so the core begins to oscillate. Over time, this small perturbation becomes large and when the star explodes its core will have additional momentum in some direction, which is observed as the kick.

This velocity has been calculated using the obtained kinetic energy of the pulsar and substituted in Eq. (1) while the pulsar mass was taken as 1.4M$_\odot$ (a typical mass of a pulsar). The resulted velocity (v_o) is equal 125$\mp$ 20 km. s^{-1}, however, as the Crab nebula tilted about 30^o from our line of sight [4] subsequently the kick velocity will be given by:

$$v_k = v_o\ \cos 30^o \qquad (3)$$

So it will be ≈110 $\mp$ 20 km. s^{-1}. This shows a good agreement with the result of Loll 2010 [4] that found that the kick velocity equals 140 km. s^{-1} using equation relating proper motion to transverse velocity.

This kick velocity will accelerate the remnant in all direction but with different rate, from Fig. 1 its shown that the pulsar is shifted slightly to the SE direction. This implied that the acceleration of the NW is larger than the accelerating in the SE since it lies in the same direction of the pulsar kick. This transverse velocity of the pulsar is affecting the expansion of the nebula along its long axis, and the overall gradient in ejecta density with

respect to distance from the expansion center when the synchrotron nebula initially began expanding.
According to the theoretical explanation it would have encountered a declining density gradient toward the NW but an increasing density gradient in the SE direction because the ejecta was distributed around the point of the explosion while the pulsar was “kicked” away and has been moving along with the ejecta expelled at that same velocity.
However, according to Table 1 the NW is about ≈ 1.1 times farther from the expansion center than the SE side which means that, the NW must have been swept up more ejecta than in the SE and subsequently has more density than the latter according to the following Eq. [18]:

$$\frac{n_{NW}}{n_{SE}} = \left(\frac{R_{SE}}{R_{NW}}\right)^5 \quad (4)$$

where:
n_{NW} , n_{SE} is the number density in the NW, SE direction respectively.
R_{SE}, R_{NW} is the radius of the remnant in the SE, NW direction respectively.
According to Eq. (4) the $n_{NW} = 1.61\, n_{SE}$, this density gradient in the ambient medium that caused by the kick velocity of the pulsar would lead to a deferred creation of the reverse shock in the low density region (SE) compared to the region of higher density (NW) which mean a delayed arrival of the reverse shock to the pulsar itself. Also the critical mass density of the filaments necessary to cause the R-T instability to begin should have been reached earlier in the NW than the SE.

Conclusions

From results obtained in this paper:
1. The injected energy of the pulsar to SNR, which found to be equaled (2-3) x 10^{47} erg, plays a significant role in the distribution and the morphology of the remnant that made it take ununiform shape (typically elliptical) since this energy will almost concentrate its ejection in the dipole rotational axis of the pulsar itself so it will appear to be elongated in some direction (NW and SE) more than others.
2. The kick velocity of the pulsar which is calculated to be ≈110 km.s^{-1} causes a variation in the distribution of the remnant mass density, since the region that lay in the direction of the kick (NW) will have more energy add to its expansion beside the initial energy that ejected from the dipole rotational axis of the pulsar itself which made it expand further than the other regions (as it shows in the results of Table 1) accordingly has more density than other remnant regions.
3. Due to the pulsar kick velocity, even though it’s very low compare with the average velocity of the remnant which is equal ≈1457 km.s^{-1}, the pulsar would not stay in the center of the supernova explosion but it will shifted from the center, in our case it shift to the SE direction, and with time it will leave its birth position and leave the remnant itself.

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