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Research Article

A STUDY OF TRIGGERED STAR FORMATIONS NEAR THE SHOCK INTERFACE OF W44 SNR

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ABSTRACT

This research work is based on VLBI exploration of radio astrometry (VERA) with H2O (616-523) maser line emission to trace the site of star formation within the interface of W44 SNR. It also includes the study of young stellar objects in the early phase of the evolution and the effect of the expanding bubbles towards triggering the Young Stellar Objects using infrared science archival (IRSA). Our results indicated the presence of H2O maser evidencing star forming region. Further study on the region with infrared emission shows that there is an expanding bubble of W44 SNR near the identified H2O maser. Furthermore, the distributions of YSOs from the archival data in an expanding bubble of the W44 supernova remnant indicate an evolutionary sequence which starts with class III → class II → class I objects.

INTRODUCTION

Star formation (SF) starts with the core collapse of dense region within molecular cloud in the interstellar medium due to gravitational instabilities. These instabilities can be caused by many factors which includes, Supernova explosion, Molecular cloud collision, Galactic Merger etc. In the particular case of supernova explosion, the shock waves from the explosion move into the surrounding molecular cloud, the interstellar gas rises up and compressed. Natural gravitational instability begins with the compression of interstellar clouds which makes the collapsing core to fragment into clumps of 0.1 pc ($\sim 2 \times 10^4$ AU) in size and 10 to 50$M_\odot$ in mass. The density of the clumps increases as the temperature and pressure in the centre increases at a certain point where the pressure stops the infall of more gas into the core and it becomes stable as a protostar with 1% of its final mass. It takes the clumps about 10 million years to become protostar. The protostar will start to accrete material until thermonuclear fusion begins in its core. Then interstellar wind stops the infall of new mass to make the protostar a full young star since its' mass is fixed. This process does not just occur anywhere in the space, there are sites where it normally occurs such as spiral arms, bok globule and so on (Elmegreen*et al*., 1977).Spiral arms are good example of star forming region. At the arms, the molecular clouds concentrate heavily, when the spiral galaxy begin its spiral action, it will sweep up the molecular clouds causing a collision between them at the arms. The collision enables gas cloud and dust to move into the density wave and trigger off the formation new stars. Bok Globule is another compact site of star formation; it is an opaque cloud of dense gas and dust (isolated gravitationally-bound small molecular clouds with masses less than a few hundred times that of the Sun). Bok globules are found within HII regions with a mass of about 2 to 50 solar mass, they contain molecule of hydrogen (H_2), carbon oxides and helium and also around 1% by mass of silicate dust. The Bok globules are about a light year across and contain a few solar masses (Hartmann *et al*., 2000). Star formation in bok globules can be in association with collapsing molecular clouds or possibly on its own (Khanzadyan *et al*., 2002). They can be observed as dark clouds that cast a shadow against bright emission nebulae or background stars. Over half the known Bok globules was found to contain newly forming stars (Smith *et al*., 2004). There is some mechanism which triggers star formation within dense region in an interstellar medium which include Molecular cloud collision, Supernova Explosion and Galactic merger.

Molecular Cloud Collision: Molecular clouds in the interstellar space or interstellar medium move randomly, when the clouds are in contact with another cloud or collide with one another and the collision process ignite the formation of stars. According to (Torii *et al.,* 2015) when the two categories of molecular clouds (blue or small and Red or large cloud)

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accidentally collides, a dense layer is formed by the compression at the interface of the two clouds. This compression creates a cavity in the large clouds, the diameter of the cavity is nearly equal to the diameter of the small clouds. During the collision, the small clouds stream into the compressed layer. Along with the cavity creation, massive clumps formation and subsequent high mass star formation occurs in the compressed layer, which means that the collisions between the two cloud triggers star formation.

Supernova Explosion: Supernova explosion can be caused by re-ignition of nuclear fusion in the degenerate star or by sudden gravitational collapse of the massive stars' core. During this process it releases shock wave which wraps the molecular cloud and compress its' gas, the density rise and the clumps in the post shock gas collapse under the effect of self-gravity and form stars. Supernova explosion remain the triggering mechanism that send shocked wave into the cloud at very high speeds.

Water Maser Data Analysis

The reduction of the obtained data was done with Astronomical Image Processing System (AIPS) developed by the National Radio Astronomy observatory (NRAO). The normalization of the auto corrected visibility data obtained at each station was done with AIPS task ACCOR. The task APCAL was used for the Amplitude calibration using system temperature and gain curve of each station. Doppler tracking was made for the maser emission line data using CVEL task. The fringe fitting was made on a phase reference source J1833-0812 by the task FRING. The position of the reference source was self-calibrated by repeatedly performing the task pair IMAGR and CALIB. The final phase residual solutions were applied to the W44 data, choosing the positional reference source as the phase reference. We concluded the data reduction with the determination of the absolute peak position of each maser sport using Gaussian fits applied to the CLEANED maser images.

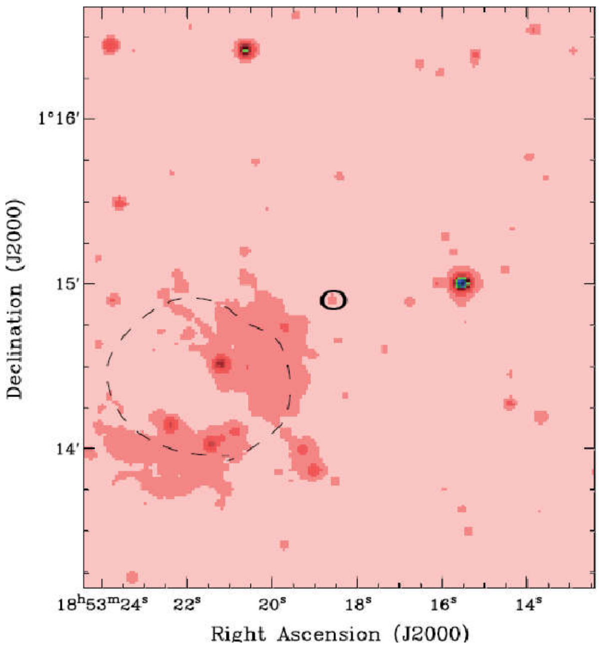

Fig 1.1 Two micron all sky survey (2MASS) infrared image showing the expanding shell of W44 with braking line and the position of H_2O maser with thick circle at the top right edge of the shell.

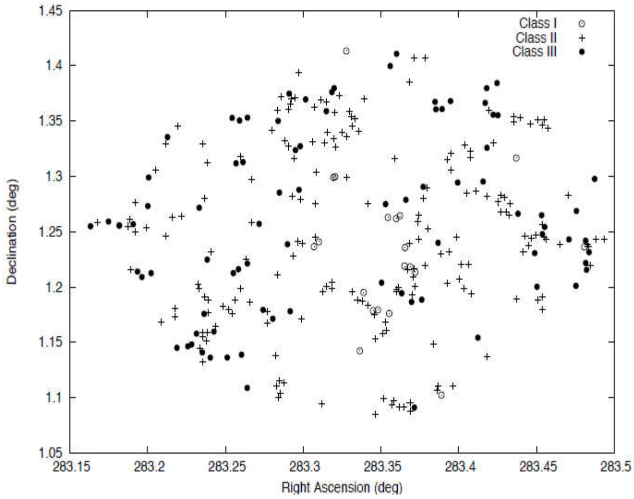

Fig 1.2 The scatter plot of the infrared data showing the distribution of different class of young stellar objects (YSO).

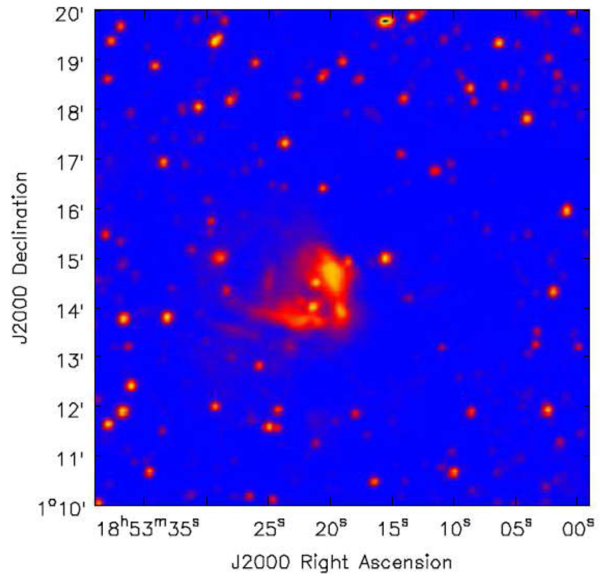

Fig 1.3 The infrared band-1 data source image. Showing the region of an expanding shell of W44 SNR with large infrared emission.

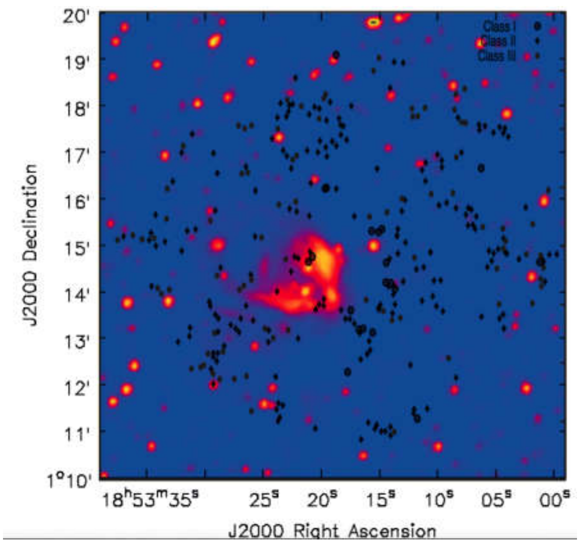

Fig 1.4 The superimposition of plotted distribution of YSOs and infrared band -1 image of the sources.

Infrared Archival Data

VERA observation reveals the position of water maser which identifies the star formation within the environment of W44 SNR, therefore we go on to investigate the region with infrared science archival (IRSA) data and obtained ALL-WISE point source catalogue of W44. The data of the point sources was of particular interest as it showed the activities of YSO within or inside the expanding bubble of W44 clearly. The data was limited to a cone of 10 arcmin of RA=283.32917, Del=+1.25000 at equatorial coordinate of α(J2000)=18h53m19s, δ(J2000)=+01d15m00s. The data obtained is made up of 1854 point sources.

Infrared Archival Data Analysis

The analysis and classification of the obtained infrared archival data was done using awk software following the command of a written awk script, the filtration of non-young stellar objects was carried out through these steps, we first checked the quality of the data and an attempt was made to remove all extra galactic sources and eliminate all active galactic nuclei (AGNs). Again, the shocks among the sources obtained was filtered out and the remaining sources were sorted manually into three categories of YSOs i.e. class I, class II and class III (Lada C.J. 1987). The distribution of these classes was plotted with the aid of software called gnu plot developed to explore data sets graphically. These classes were graphically represented with (ʘ), (+) and (•) respectively. The infrared band 1 image of the sources and the distribution plot were superimposed as a means of correlating the two data as shown in Fig. 1.4. below

VERA Observation of water (H_2O) maser

We found water maser in the environment of W44 SNR, in Fig.1.1 below, the water maser is at the shock interface of the expanding bubble and the interstellar medium (ISM), with flux of 9.251 x 105 ± 1.61 x105jy/beam. Water maser is in association with later type star tracing high densities and temperatures in the post shock gas (Seta *et al*.,1997) and NGC3576 study also uncovered water maser at the arms of filament where star formation is ongoing (Purcell *et al*., 2009).

Infrared Band-1 study

The infrared observations show that the remnant's expanding bubble triggers mainly class II young stellar objects (YSO) shown in Fig.1.4. The result is in line with Wootten (1978), whose study revealed infrared sources W44IRS1 and W44IRS2 possessing spectral features in protostellar objects. W44IRS1 is an example of supernova induced star forming region associated with W44 SNR which is a star just after its formative stage and it is closed to W44 SNR expanding into dense materials surrounding the star. The energy distribution, color temperature and absorption feature are similar to the protostellar sources embedded in molecular cloud (Williams, 1977). Again, the eastern edge of W44 SNR was covered by young stellar objects, molecular cloud and HII regions.

Young Stellar Objects Distribution Study

We found about 287 young stellar objects from the 1854 source that we extracted, these 287 sources which are YSOs are classified into three classes. 19 sources are class I, which Lada (1987) described its spectra index to be greater than zero $\alpha > o$. 187 are class II which is more in number than other classes and the remaining 81 sources are class III. The spectra index of class II is -1.5 <α< 0 and class III is α< -1.5. Class I are represented with ʘ, class II with + and class III with •, there spectra index was proposed by lada (1987). According to him class II which are more in number are young low mass star approaching the main sequence. He pointed out that these young stars have circumstellar disk which suggest the possibility of accretion.

Water Maser as an Indicator of Star Formation

In the Vera observation, we chose to trace star formation site with H_2O maser, The H_2O maser at the coordinate α (J2000) = 18h53m19s, δ(J2000) = +01°14'58'' was found at an interface of the expanding shell of W44 SNR in the 2MASS k-band image (Fig.1.1) below, the H_2O maser is exactly at the same position with an infrared point source indicated with thick dark cycle. The breaking lines indicate the region of an expanding bubble of W44 SNR. When the remnant W44 expands it compresses the post shock gas towards the position of the H_2O maser. Recall that this type of maser was discovered in various astrophysical objects like star forming region, supernova remnant etc and it is a good instrument to study its environment. The presence of H_2O maser at the position indicates the site of star formation. The result of the first phase of this work implies that within W44, there is a tendency that star formation is ongoing, because of its close associate with H_2O maser. This agrees with Furuya *et al*. (2011) that the emission from H_2O traces part of protostellar disk and collimated outflow in high mass star formation region.

Expanding Shell of W44 Triggering YSOs

The second part of this work is the use of IRSA to investigate the environments of W44 in which H_2O maser has been detected. We use All- wise source catalogue which reveals the distribution of sources, and an infrared image of the sources which clearly show the expanding shell or bubble of W44 SNR. Fig. 1.2 shows the scatter plot of all the young stellar objects of about 287 out of 1854 source extracted. The YSOs were distributed as follows 19 are class I young stellar object, about 187 are class II, while 81 are class III objects. We represented class I withʘ, class II with (+) and class III with (•). The region with large infrared emission in Fig.1.3 represents the expanding bubble of supernova remnant. Then after we overlaid Fig. 1.2 and Fig. 1.3 it resulted as shown in Fig. 1.4. Therefore, within and outside the region of expanding bubble of W44 SNR in Fig. 1.4, there are YSOs marked with cross sign (+), dot (•) and zero with dot inside (ʘ). Theexpansion of supernova remnant compresses the objects surrounding it at different region and makes the density, temperature and pressure of the region to increase and could trigger off star formation. In the distribution, we observed that class II is far more numerous than other classes both inside the region of an expanding bubble and outside it. Within the region of expanding bubble, there are three shells of YSOs, the outer shell represents class III which is the oldest class, the middle shell is class II which is older than the inner shell (class I) observed to be the youngest and the last to form. From these observations, the class III is the first product of the expansion followed by class II and then the primitive class I objects which is invisible stars. The findings imply that the expansion of the remnant W44 trigger star formation as it shocks and expands. The first shock occurs at inertia state of the remnant, so with low gas it produces class III, second shock occur when it has gathered more gas and produces class II. Class I objects was triggered when the gas acquired in the second shock was limited. For the fact that class II objects were triggered with more gas and associated with low mass T Tauri star, it become more numerous than other classes. So, the expanding shell of W44 triggers mainly class II. This generally implies that W44 supernova remnant constitute a conducive environment for the formation of YSOs.

W44-IRS1 offers compelling evidence that it is a star whose formation was recently induced by expansion of the supernova remnant. W44-IRS2 lies beyond the remnant, possibly apart from the region of its influence (Wootten 1978).

This is inferred because the presence of H_2O maser creates an enabling environment for stars to be born.

Summary

Stars are the fundamental objects of the universe, the home of planetary systems. They provide the necessary energy for the development and maintenance of life. The formation of star has been the subject of many astronomical researches. Star formation takes place deep inside of an interstellar cloud (Kwok *et al*., 2006). The region of star formation had been indicated by many researchers. This work investigates the site of star formation around W44 SNR. After investigating the entire environment of W44 with H_2O maser data from VERA and infrared data from IRSA, we report the possibility for the expanding action of W44 to trigger star formation. The VERA observation analysis shows an indication of Star Formation site while the infrared investigation reveals stars at its primitive stage (YSO), and the sequence of its formation. Direct observation of the star formation process and the development of a theory to explain it have been severely hampered by the fact that most stars form in dark clouds and their formative stages are invisible optically. Advanced technology however opened the infrared and millimeter windows to astronomical investigation which enabled direct observation of star forming regions.

The relatively young age of W44 derived from its associated pulsar, (~ 2 x10^4yr) (Wolszczan *et al.,* 1991), and the spectral type of its progenitor seemed to show that the current star forming process in the region had not been triggered by SNR alone. It is also noted that star formation can be initiated by the expansion of an HII region in different ways (Elmegreen *et al*., 1998). The distribution of the various classes of YSOs in the expanding bubble with class III objects in the outer shell followed by class II in the middle shell and then class I in the inner shell indicates an evolutionary sequence in star formation in the region.

CONCLUSION

In this research we viewed our VERA observational result in comparison with 2MASS infrared image of W44 and discovered the position of H_2O maser which indicates the star formation site. In other to ascertain what is happening in the region where H_2O maser was found, we explored the infrared data of the point source in the masing region as described previously, the infrared data show numerous sources of YSOs which we plotted and compared with their infrared emission image. The two observations gave a clear understanding that the region of interest (W44) possibly is triggering star formation. We propose that the YSO formed through the sweep-and-collapse effect were triggered by the expanding shell of the W44 SNR. The information we have to support this result was the age of the star is about 10^4 years and a luminosity of 10^3L_* and W44 is known to be a middle-aged SNR of age 2×10^4 years (Giuliani *et al*., 2011). The age of the YSO and its spatial position also support the fact that the YSO might have formed through the triggering effect of the SNR.

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