The radio evolution of NGC 7027

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Planetary nebulae

Planetary nebulae are unusual objects. They come from low mass, faint stars yet are among the brightest objects in a galaxy. They are gaseous nebulae with diameters of typically around 0.1 pc, and form during the transformation of an evolved star to a white dwarf. At this transition, between 20% and 80% of the mass of the star is ejected in a slow but catastrophic wind. Eventually, the star begins to evolve down the white dwarf cooling track, while the expanding nebula will merge with the interstellar medium. This evolution, from the ejection of the nebula to its fading and disapperance, lasts only between 10^3 and 10^5 yr: it is the fastest (non-explosive) phase of stellar evolution, and one where measurable evolution may be expected within human time scales.

The brightest planetary nebula, mainly because of it's youth and proximity, is NGC 7027. It has a compact ($10''$, dense ($10^5\,\mathrm{cm}^{-3}$) ionised nebula, within a much larger molecular envelope. The radio flux is as high as 6 Jy, sufficiently bright to be one of the standard sources used to define the flux calibration at radio wavelengths.

NGC 7027 has been observed regularly at the VLA, starting in the early 1980's. The expansion of the nebula was measured directly by Carl Masson in 1986, as 4.7 milli-arcseconds per year.

NGC 7027 was also included in a long-term project to monitor all objects used as primary flux calibrators, in order to improve our knowledge of the calibration scale. As of now, we have monitored NGC 7027 for almost 25 years. The result has been surprising: we detected its fast evolution, and incidently obtained one of the most accurate masses ever measured for a single, non-pulsating star.

Evolution

The radio spectrum shows two distinct regions. At wavelengths longer than 5 cm, the radio flux is self-absorbed within the nebula. In this optically thick region, the radio flux is proportional to the

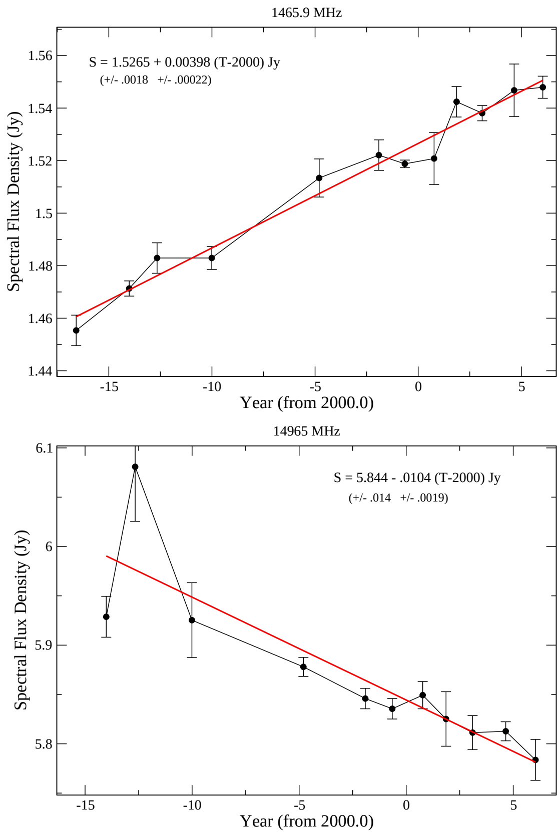

Figure 1: NGC 7027 radio flux evolution at 20 cm (optically thick regime) and at 2 cm (optically thin regime).

projected surface area of the nebula. At shorter wavelengths, all radio emission generated in the nebula escapes: here the radio flux is proportional to the number of ionisations per second, i.e. the number of ionising photons per second emitted by the central star.

The radio monitoring shows a notable *increase* over time of the flux in the optically thick region. This is illustrated in Fig. 1 for a wavelength of 20 cm. At the same time, at optically-thin wavelengths the flux is *decreasing* (Fig. 1, lower panel). The physics behind this contrasting behaviour provides an unexpected clue to stellar evolution.

Expansion

The increase at 20 cm, of $0.26\%\,\mathrm{yr}^{-1}$, is due to the physical expansion of the nebula. It directly measures the increase in projected surface area. The nebula is eliptical, and expands somewhat faster towards the poles than towards the equator. The observed expansion depends on the velocities and on the distance. Using the best determinations for the velocity field, we can derive the distance. A correction of about 10% needs to be made, because as the nebula expands, the ionisation front advances slightly faster than the gas itself (so that the ionised mass increases over time).

We produced various geometrical models for the nebula: a tilted cylinder, and a prolate ellipsoid. These predict an almost identical expansion of the surface area, by a fraction of $0.20\%/(d[\mathrm{kpc}])\,\mathrm{yr}^{-1}$, where d is the distance.

Correcting for the differential movement of the ionisation front, we derive a preliminary distance of $d \approx 860\,\mathrm{pc}$. The angular expansion is a factor of two more accurate than from the previous direct measurements; the dominant source of uncertainty is now the velocity field.

Fading

At short wavelengths, there is a clear and unexpected fading of the nebula. The optically thin radio flux arises from free-free interaction between electrons and charged nuclei (mainly hydrogen). To a good accuracy, it is proportional to the ionisation rate. The thick molecular envelope indicates that NGC 7027 is opaque to ionising photons in all directions. Thus, the number of ionisations measures the number of ionising photons emitted by the star.

We find a decline in the optically-thin radio flux of $-0.15\%\,\mathrm{yr}^{-1}$. This decline shows the evolution of the central star. The star is known to be hot ($T_{\mathrm{eff}} \approx 160\,000\,\mathrm{K}$). The number of ionising photons is dropping for two reasons. Firstly, the star is located at the tip of the white dwarf cooling track: it may have just begun its decrease in luminosity. Second, and in apparent contrast to this, the star is still increasing in temperature, giving a decrease in ionising photons as the energy per photon increases. We find a change in temperature of $85\,\mathrm{K}\,\mathrm{yr}^{-1}$, and a change in luminosity of $0.10\%\,\mathrm{yr}^{-1}$, where we relate these two quanities using the evolutionary models from Thomas Blöcker.

The same models predict that the speed of evolution is a very strong function of mass of the star. A good fit of the fading of the nebula is found if the mass of the star is $M = 0.636 \pm 0.009\,\mathrm{M}_\odot$. The quoted uncertainty is based on observables only: allowing for uncertainties in the theoretical predictions will increase the errors to $\sim 0.02\,\mathrm{M}_\odot$. Few stellar mases have been measured to such accuracy.

The original mass of the star is around $3\,\mathrm{M}_\odot$: the difference with the current mass shows the effect of the catastrophic mass loss which ended about 1000 yr ago.

Fig. 2 shows a representative model, with a stellar mass of $0.644\,\mathrm{M}_\odot$. This mass is within the range of uncertainty of our determination. The evolutionary track in the HR diagram is shown, as well as the luminosity and temperature as function of time. The rate of luminosity change is roughly constant, and the temperature increase will slow down a bit, over the next 500 yr. A very sudden luminosity drop will occur at the time the peak temperature is reached. We predict that the current evolution will proceed at an approximately linear rate until this point is reached. The time at which it is reached is again very sensitive to mass, and once determined will allow us (or future generations) to further improve the mass accuracy. The timing depends on the current temperature of the star and on its mass.

Flux scale

The radio spectrum of NGC 7027 has been measured over a range of wavelengths between 1 and 20 cm. A photo-ionisation model was used to fit these flux densities, as well as the optical spectrum and the changes in the radio flux over time. A consistent fit is obtained over the full range of wavelengths. The differences with the observed flux are around 1%. However, these differences appear to be consistent over time at each wavelength. This may indicate errors in the radio flux scale as adopted at the VLA. Agreement to 1% is very encouraging for the current accuracy of the scale, however.

NGC 7027 remains an excellent flux calibrator for all radio telescopes where its structure is not resolved out. The current monitoring has provided accurate relations for its flux density evolution over

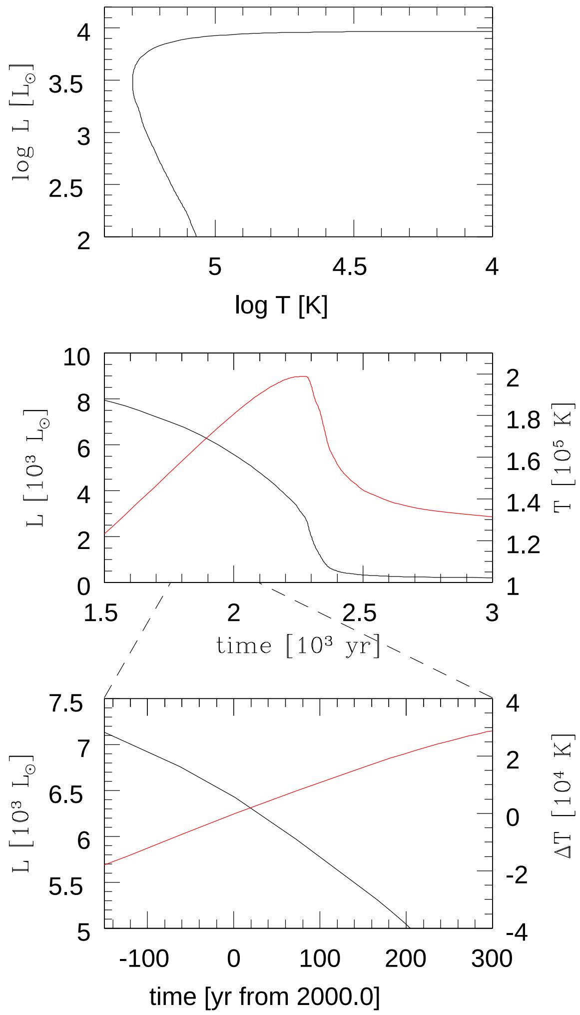

Figure 2: Predicted evolution of NGC 7027. Top: the HR diagram. Middle: the black line shows the luminosity versus time, and the red line the temperature versus time, over a 1500-yr period. The sudden acceleration of the evolution at the time of peak temperature is clearly visible. Bottom: the predicted short-term evolution.

time, which are expected to hold for several decades. Predictions of this order are unusual in astronomy, but we have no reason to expect second-order terms to become important before the peak temperature is reached. Once deviations are found, these will provide unique constraints on the late phases of stellar evolution.

Summary

Monitoring of NC 7027 has given a clear picture of its expansion and evolution. The stellar mass has been determined to a very good accuracy, and the distance is now known to within some 10–15%. The latter can be improved with a better velocity field. Seeing real-time evolution is rare in astronomy: although everything in astronomy evolves, whether stars, galaxies or the Universe, this evolution normally occurs at an indiscernable rate.

The models predict that the observed evolution will continue at an approximately linear rate. Eventually, the star will reach a peak temperature, after which it will begin to cool down and also will fade much more rapidly. We predict that this will happen within 100–1000 yr. Whether it will still be the VLA which will detect this event can be debated–but for astronomers with some patience, there is a future in radio astronomy.