Supernova Remnants: What Do They Tell Us about Massive Star Evolution and the Interstellar Medium?

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Ever since that spectacular death of a heavy star in the constellation Taurus was recorded in ancient China, astronomers have wondered about what really happens when a supernova explodes. It is true that the discovery of pulsars has brought us a long step forward, but there are still many mysteries to be solved. Dr. Michel Dennefeld, of the Scientific Group in Geneva, reviews our present knowledge and shows how the study of supernova remnants may eventually lead to a better understanding, not only about a supernova itself, but also about the surrounding interstellar medium.

Like many other objects in the sky, the study of supernova remnants (hereafter called SNR's) has greatly benefitted in the last few years from the increased technical possibilities, both in sensitivity and in spectral range. Interestingly enough, the only objects which were already studied in some detail in the 1950's or earlier, namely the Crab Nebula, the Cygnus Loop and Cas A, are now known to be representative each of a different aspect of the SNR's: Cas A is a young SNR believed to have been born around 1670, the Cygnus Loop is a much older remnant (around 20,000 years old) whose aspect is due to strong interaction with the surrounding medium, and the Crab, while young, is peculiar (still the only object definitely known in its category) because the pulsar in its centre is the active source of energy for the surrounding nebula.

The Evolution of SNR's

The dynamical evolution of an individual SNR shell can be conveniently divided into four phases. In the first phase, the ejected material is expanding freely and the situation is governed by the properties of the initial explosion. But as soon as the expanding shock-front has swept up a mass of surrounding interstellar material of the same order as the ejected mass, this heated interstellar medium starts to dominate and the SNR enters phase 2, which lasts as long as the integrated losses of energy are negligible with respect to the initial energy (this phase is therefore also called the *adiabatic* phase). When this is no longer true, we are in phase 3 where radiative cooling losses are important. The matter that passes through the shock-front cools rapidly, the density becomes high and a thin shell is forming, which can be considered to move with constant linear momentum. The thermal energy in the object is now small compared to the kinetic energy (this phase is also called the *radiative* phase). In the last phase, the expansion velocity becomes comparable to the thermal or random motions in the surrounding interstellar gas and the SNR gradually loses its identity. Knowing some initial parameters: energy and mass released by the SN explosion, the density of the surrounding medium and the magnetic field, the above simplified model can predict how the shock velocity, the density and the temperature behind the shock will evolve with time. These predictions must be compared with the available observations: in the optical, X-ray and radio range. Indeed the initial parameters are generally not known for an individual object, with the resulting difficulty that the classification of the object with respect to the four phases is not known precisely.

Expansion Ages

In our galaxy, less than 30 out of the 120 recognized radio SNR's have detected optical counterparts. Only a few of them exhibit the "classical" regular shell structure. However, this is not surprising because very *young* or very *old* remnants would only show a few thin filaments or a rather diffuse structure, like Cas A or Monoceros SNR, respectively, and also because a regular shell can only be formed by propagation in a homogeneous surrounding interstellar medium. In the case of very young remnants, when the velocity of the filaments is still very high, the combination of radial velocity and proper motion measurements can yield the distance of the object and its age with the assumption of uniform expansion. As an example, the optical filaments in Cas A, consisting of fast-moving knots (up to 9,000 km/s) and quasi-stationary filaments, have yielded an age of only 300 years (from the fast-moving knots), although this "historical" supernova was in fact not observed in the 17th century (but the measured extinction of 4.3 magnitudes in that direction could explain why). The quasi-stationary filaments have given an age of 11,000 years, therefore pointing towards a milder release of this material. For the Cygnus Loop, with measured radial velocities of the order of 100 km/s only, one gets an age of 60,000 to 100,000 years.

Abundance Determinations

However, the major interest of the optical filaments in SNR's is the possibility of making a detailed spectral analysis with particular emphasis on abundance determinations. The spectrum consists generally of emission lines of the most abundant atomic species in various ionization stages: H, He, N, O, S, Ne, as in other gaseous nebulae, with little or no detected continuum. But the major difference from the spectra of H II regions or planetary nebulae, although not recognizable in a straightforward way, is that in SNR's the elements are ionized by collisions (an effect of the shock-wave) while in the other nebulae the ionization is due to absorption of radiation from the central star(s). This must be taken into account when doing the abundance determinations. The abundance of a given *ion* can be derived in a straightforward way with respect to, say, hydrogen, by measuring the corresponding relative line intensities (for example the relative abundance of O^{++} to H^{+} comes directly from the intensity ratios of the 5007 [O III] line to Hβ) if the electronic temperature and density are known (from specific line intensity ratios).

But to go from this to the relative abundance of the *atomic* species requires the knowledge of how much of the oxygen, in our example, is in other forms than O^{++} (O^{0}, O^{+} or higher ionization stages), that is, to know the complete ionization structure. While this is generally done by model calculations trying to reproduce the observed spectrum in the case of H II regions, very few such models have been done yet for SNR's. However, these few models, by reproducing more or less correctly the observed spectrum of for instance the Cygnus Loop, have at least proven the validity of the hypothesis: ionization by collision and *not* (or only in a small fraction) by radiation. Furthermore, these complicated models (one has to solve simultaneously the hydrodynamical equations for the propagation of the shock-wave and the cooling equations) have shown that the temperature in the emitting region must be lower than in H II regions or planetary nebulae. This is confirmed by the observation of lines of low-ionization species like O I, S II or Ca II which are much fainter in other gaseous nebulae. This can then be used as a criterion to distinguish SNR's from other objects (see Fig. 1).

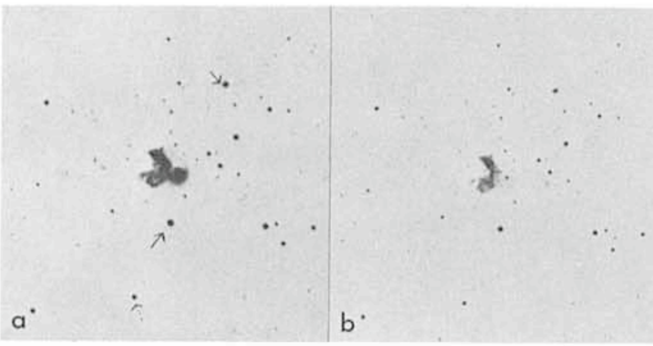


Fig. 1. — *Two plates taken by Dr. Barry Lasker with the CTIO 4 m telescope of N 63 A in LMC. Fig. 2a is an Hα picture, while Fig. 2b is taken through a [S II] filter, a characteristic emission of SNR's. The SW part, not appearing in [S II], is probably an ordinary H II region.*

Waiting for more model calculations, we may proceed with abundance determinations as long as we see lines of different ionization stages of the same element in the spectrum (a typical example is oxygen, for which we have [O I], [O II], [O III] lines), making possible an empirical estimate of the ionization equilibrium. In this way, for example, the fast-moving knots in Cas A show an overabundance of O and S by more than 50 (in mass) over the cosmic values, clearly demonstrating that we see material which has been processed in the core of a massive star. The overabundance of the "Si group" elements (Si to Ca) shows that O-burning has probably taken place and that the star must have been rather heavy, at least 20 solar masses ($M_\odot$). On the other hand, the quasi-stationary filaments in Cas A are overabundant in nitrogen by a factor of 10 with respect to hydrogen, while very little H is present in the fast-moving knots. This shows that we see here material having been processed via the C, N, O cycle and which was released through mass loss in the presupernova star (some 11,000 years before the SN explosion). This is consistent with the time elapsed between core C burning and core collapse and requires also a star of about 20 $M_\odot$.

Young SNR's are therefore a direct check of massive star evolution models. With older remnants, where substantial mixing with the interstellar medium has occurred, the abundance analysis would refer to this material only. A striking example is given by the SNR's in the Magellanic Clouds, where we find an underabundance of nitrogen with respect to hydrogen (compared to Orion) of a factor of 4 in LMC and 10 in SMC, fully consistent with results from H II regions and planetary nebulae. Similarly, the recently discovered SNR's in M 33 yield an underabundance of a factor of 2 in N; the same is found in nearby H II regions. We are therefore directly testing here how the interstellar medium has been enriched by processing to several generations of stars. The only young extragalactic SNR known up to now is N 132 D in LMC (see *Messenger* No. 5) which effectively shows a large overabundance of oxygen, making it a case very similar to Cas A. Abundance analysis will probably be extended in the near future to species not observable in the visible range of the spectrum, like carbon, by going to the near IR and to the UV with the new facilities now available.

X-ray Observations

The extension of the investigation of SNR's to the X-ray range has already greatly improved our understanding of their evolution. There are now 7 certain identifications of SNR's in X-rays in our galaxy, and some 10 possible or probable. Only one is possibly identified with an extended X-ray source in LMC, but needing confirmation. In general, the younger the remnant, the harder are the X-rays when detected. The observed spectrum is always compatible with a thermal origin. While there could still be some hesitations between thermal spectrum and power-law spectrum because of the uncertainties in the data, the detection, in some cases, of a Si XIV line in X-ray or a Fe XIV line in the visible strengthens the hypothesis of thermal bremsstrahlung, originating in the hot plasma behind the shock-wave. The derived temperatures are of the order of a few million degrees. As the X-ray luminosity is a well-known function of temperature and density of the emitting plasma, the measured absolute flux gives immediately the density (if the size is known). These values can then be inserted in the equations derived from the above model to get the inital energy and the age of the remnant. The mean value of initial energy is found to be $5 \cdot 10^{51}$ ergs for a surrounding density of 1 cm^{-3}, compatible with what is derived from the luminosity of supernovae.

But the surprising fact is that the derived ages are, for the older remnants, much shorter than those derived from the observed velocities in the filaments. This leads to the realization that the optical filaments we observe are probably not representative of the shocks as a whole, but are just those parts having encountered a higher-than-average density in the surrounding medium. For instance, the "X-ray" age of the Cygnus Loop is about 20,000 years (instead of 60,000 or more as derived from the optical filaments), which would still put it in phase 2 and not in phase 3. One therefore wonders whether a given phase can at all be ascribed to a whole remnant: certain parts, having been more decelerated than others, may already be in the radiative phase, while others, as demonstrated by the high temperature X-rays, are probably still in the adiabatic one. Indeed, new attempts to detect fainter filaments in the Cygnus Loop have revealed their existence with velocities two to three times higher than the previously known strong filaments. These problems of inhomogeneity are now being introduced into the models, together with the effects of inward-propagating shocks resulting from the interactions of the initial blast-wave with the surrounding medium. That such complicated phenomena do indeed occur is shown by the illustration (Fig. 2).

Radio Observations

The origin of the non-thermal synchrotron radio emission from SNR's, while being the first criterion for identification of a SNR, is still not understood. A large effort has been made in mapping the sources, showing that the radio shells in general are more complete and uniform than the optical patches and that the superposition with optical features is normally very good. Polarization maps show the magnetic field to be orientated radially in the young remnants (Cas A, SN 1006, Tycho) and tangentially in the older ones (Cygnus, W 44). This is consistent with the idea that the shock-wave plays a role in compressing the magnetic field: but *which* fraction is inherent to the SNR, *which* fraction is compressed interstellar magnetic field, and *where* are the high energy electrons coming from, are still unanswered questions.

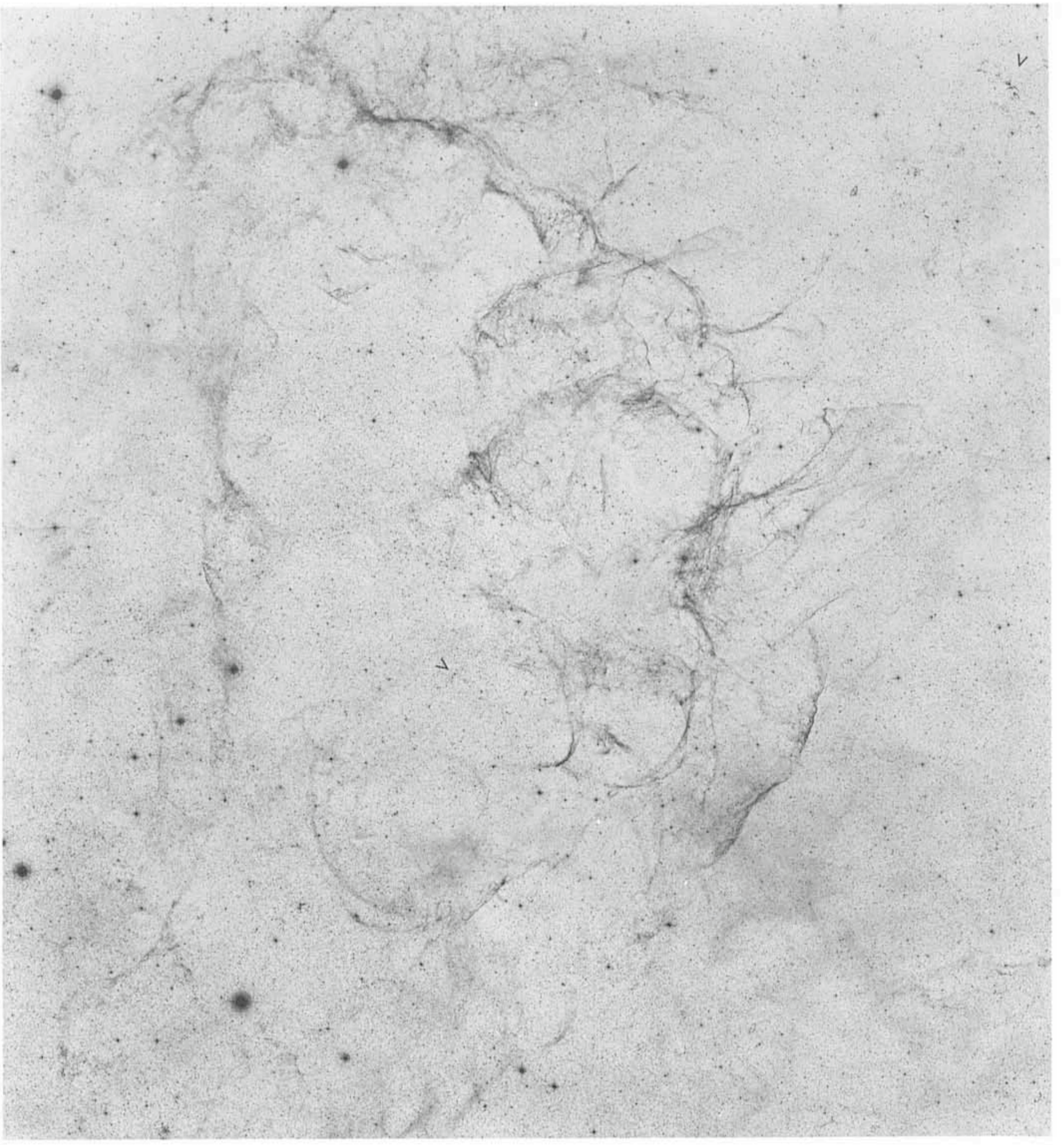


Fig. 2. — *A 90-min red plate, 098-04 + RG 630, taken with the ESO Schmidt telescope by H.-E. Schuster, of the Vela Supernova Remnant. It shows the complex structure resulting from interaction of a shock-wave with an inhomogeneous interstellar medium. The age is estimated to be about 12,000 years. The central arrow shows the approximate location of the Vela pulsar. The arrow in the NW corner shows the Puppis SNR, which exhibits strong [N II] lines. Did it explode in an already enriched surrounding medium?*

The Frequency of SN's

However, if the individual radio evolution is not yet completely understood, the large number of known radio SNR's in our galaxy provides a statistically significant sample to estimate the mean interval between SN explosions. The linear diameter of SNR's can be estimated from the empirical relation between radio surface-brightness and diameter, calibrated by some remnants with well-determined distances. Then the histogram of diameters can be used, either with some age calibrators or by trying to fit it to the theoretical evolution curve, to determine the frequency of SN events. One finds a mean interval of 75 to 150 years, depending on the assumed completeness of the catalogues. This has to be compared with a mean interval of 11 years found from historical SN's (however with large correction factors (or 10 to 30 years found from statistics of SN's in external galaxies, depending on the type, Sbc or Sb, that is attributed to our galaxy.

Clearly, the discrepancy is large enough to look for other factors. It should, however, be stressed that a mean interval of 10 years would imply that stars more massive than 3 $M_{\odot}$

should explode as SN's, while 75 years would give a lower limit of 9 M☉, all compatible, within the errors, with the ideas about massive star evolution. No additional constraints can be set up from pulsar birth-rates, because of the large uncertainty in the evaluation of the maximum age of a detectable pulsar. This age is at least a factor of ten higher than the assumed maximum age for a detectable SNR (approximately 10^5 years) and is probably enough to explain why, if about 300 pulsars are now detected, only two firm associations between pulsars and SNR's have been made: the Crab and Vela, both young objects. The detection of such associations is in addition made difficult by the large transverse velocities now measured for some pulsars.

The same kind of comparison between SNR statistics and massive star evolution has been tried recently for LMC. Owing to the large uncertainties involved there: uncompleteness of the SNR sample and no firm independent knowledge of what the SN rate should be, one can only conclude that the number of observed supergiants compared to the best estimates of the SN rate is compatible with the idea that the minimum mass for a SN progenitor lies somewhere between 4 and 8 M☉. But, both in LMC and in our galaxy, it remains to be explained why so few SNR's of diameters larger than about 30 pc are observed, while this corresponds, according to the present views, to only about one-tenth of the expected life time. As most of the SNR's are detected at radio wavelength, a better understanding of the relations between the radio emission and the surrounding medium may help to solve that aspect of the problem.

Further Research Needed

Not very much attention has been given in this review to the Crab Nebula. It reflects, in fact, the work on SNR's in the last years, where the Crab was believed to be understood, at least as far as the mechanism of excitation of the visible filaments was concerned, and also regarded as being too peculiar by comparison with other SNR's. However, things are changing now. A search is under way for fainter filaments outside the main nebula which may be the tracers of the shock-front and some new possible members of the same morphological class as the Crab are being found (3C 58, G21.5-0.9). Other trends of present research include the search for older, large-size SNR's in our galaxy and LMC, with the difficulty of distinguishing them from H II regions or other shock-excited nebulae (stellar winds); detailed investigation of velocity structures to be compared with models; extension of the studied spectral range to the UV and near IR; search for SNR's in other galaxies of the Local Group mainly by optical techniques (see Fig. 1), and last, but not least, investigation of nuclei of external galaxies showing the characteristic emission lines of low ionization species, in order to see whether or not there is any significant contribution of shocks in the excitation of these nuclei. There is great hope that, with the simultaneous development of model calculations, all this effort will eventually answer the remaining major questions about SNR's and their progenitors. And we may at the same time learn as much about the surrounding interstellar medium as about heavy element processing in massive stars.

A New Infrared Top-end for the 3.6 m Telescope

So far, most, but not all, infrared observations have been carried out with conventional optical telescopes. This often implies that a comparatively strong infrared radiation (heat) from the telescope proper has to be subtracted from the total signal for a given celestial infrared source. This is particularly so when the telescope has much material in the beam, e. g. support of the secondary mirror, cables, etc.

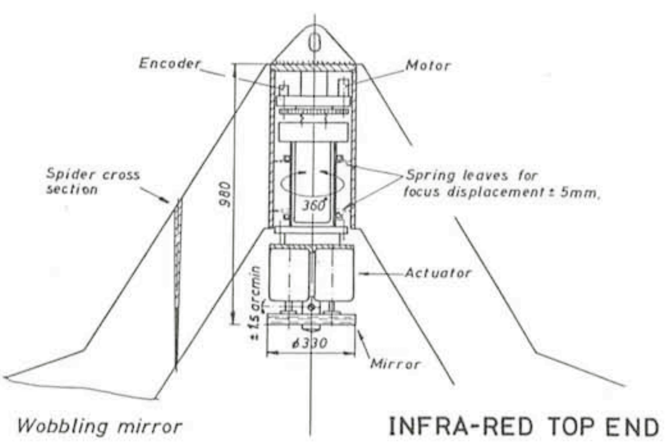
This problem was taken into account when the 3.6 m telescope was designed. It has interchangeable top-units, each specifically built for its purpose. ESO engineers Wolfgang Richter and Rolf Grip have now started designing the new infrared top-unit. This is a brief status report about that project:

The infrared top-end for the 3.6 m telescope is composed of two units:

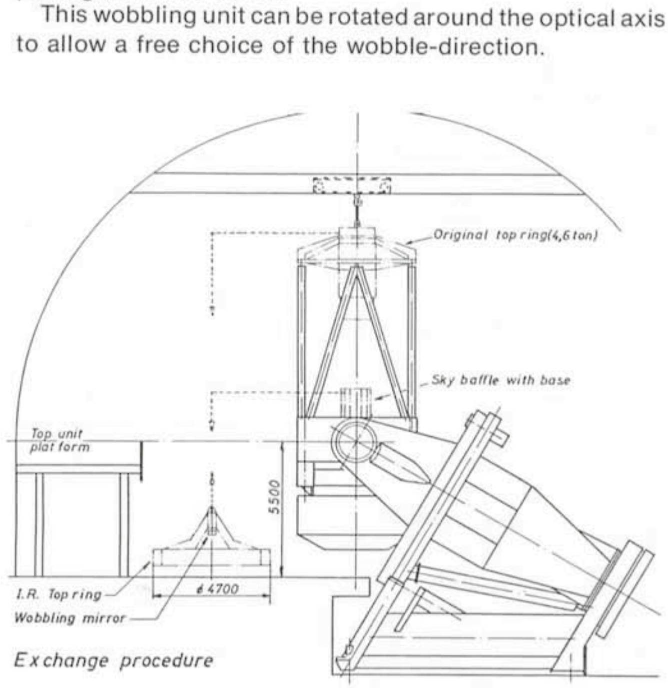
- wobbling secondary mirror
- top-ring for infrared observation.

The design of these two units is actually in progress. The optical conception is a secondary mirror for an f/35 at the Cassegrain focus. This secondary mirror will be excited by two electromagnetic actuators, one pushing, the other pulling, and vice-versa.

This wobbling unit can be rotated around the optical axis to allow a free choice of the wobble-direction.



Wobbling mirror



Exchange procedure