MASS LOSS FROM NOVAE AND SUPERNOVAE

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ABSTRACT

The physics of mass loss from these objects is reviewed. Both winds of different types and nearly instantaneous ejection are involved. Supercritical winds driven by the pressure of radiation from an object above the Eddington limit, probably exist for novae after their outbursts. Observations outside the optical region and in particular in the satellite UV have been very important.

I shall talk about processes which are far more violent than the mass loss of more ordinary stars. Both sudden explosive mass loss and very violent winds are encountered. They are perhaps useful in understanding more gentle processes of mass loss, and in any case play a major role in the evolution and in particular the chemical evolution of the galaxy.

The stars which shall be considered undergo, sudden explosive brightenings, of the order of 10^4 - 10^5 for many novae. Supernovae reach maximum visual fluxes of about 10^4 times more than those of novae. The brightenings are quite sudden, while the fadings are slower. A nova normally brightens a factor of about 10^4 in several hours and fades over months or years. Similarly observations indicate a rapid brightening of type I supernovae in a few days. The rate of fading is used to distinguish "fast" and "slow" novae, defined in a somewhat arbitrary fashion as fading 3 magnitudes in less than 100 and more than 150 days after maximum respectively.

I. NOVAE

a) What type of star is involved

Novae like other kinds of cataclysmic variable (dwarf novae, etc...) appear to be all interacting binaries. A white dwarf accretes

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material from a cooler companion filling its Roche lobe, and usually quite near the main sequence. Accretion is generally through a disk, which may however in some cases be broken up near its centre by the magnetic field of the accreting star. The gas stream from the companion, encounters the disk in a bright spot.

Nova explosions are generally thought to be associated with thermonuclear runaways in the accreted material, which is rich in hydrogen. The classical theoretical work has been reviewed by Starrfield et al. (1976), Sparks et al. (1977) and by Gallagher and Starrfield (1978), where one sees that runaways are possible following accretion on to a degenerate star. Such concepts have a number of consequences, among which one should mention :

1) Nova explosions are recurrent. Fresh gas is accreted after an explosion leading to another explosion. Using statistical arguments Bath and Shaviv (1978) found a recurrence period of 10^5 years for classical novae, while the so-called "recurrent novae" have according to these authors, recurrence periods of the order of 30 years, because they have giant companions associated with much higher accretion rates near 10^{-6} $M_\odot$/year. However the situation is more complex. For instance some recurrent novae are now known not to have giant companions, while recent work based on IUE ultraviolet spectra (Friedjung et al., 1982) indicates that even the apparently classical old nova HR Del has at present a very high accretion rate of 10^{-6} $M_\odot$/year ; this rate probably cannot be maintained for long times after the explosion. In any case new theoretical work of Prialnik et al. (1982) indicates that nova like outbursts only occur below a maximum accretion rate between 10^{-8} and 10^{-9} $M_\odot$/year.

2) Non cosmic abundances can be expected in the ejected material. Initial CNO enhancements are necessary to obtain a fast nova outburst. In addition the decay of β^+ unstable nuclei in layers ejected, when they are too cool for further proton captures, results in isotopic ratios not characteristic of equilibrium burning at any temperature. Nevertheless slow novae do not need initial CNO enhancements in the stellar envelope and can usually have roughly equilibrium isotope ratios but non solar abundances in their ejected material, as shown by Prialnik et al. (1978).

The predictions of non cosmic abundances in the material ejected by novae are supported by observation. In particular abundance analyses of the nebulae formed by the ejected gas long after the explosion (Collin-Souffrin, 1977 ; Ferland and Shields, 1978 ; Ferland, 1979 ; Williams et al., 1978 ; Stickland et al., 1981), indicate CNO and also helium overabundances, the result of the last reference being based on ultraviolet data. Results obtained at earlier stages of the development after a nova explosion (Antipova, 1974) from absorption spectra, lead to similar conclusions, though the physical basis of the interpretation is less certain. Even nebular abundances can be wrongly estimated in the presence of X-rays (Ferland and Truran, 1980). It may be also noted that Williams and Fergusson (1982) even find high helium overabundances in the accretion disks of several cataclysmic variables including the old nova V 603 Aq., but doubts can be raised concerning the interpretation of the observations.

b) Processes after nova explosions

Observations of novae after their explosive brightenings indicate that complex processes occur. Until ten years ago there was little evidence that theoreticians and observers spoke about the same objects ; even now many problems of theoretical interpretation remain.

When one examines the spectrum of a nova soon after light maximum in the optical domain one sees lines having profiles which can be considered the result of superposing several P Cygni type profiles. There are a number of violet shifted absorption components, with central emission. The absorption components of different lines belong to "absorption systems", each having a certain Doppler shift at a certain time. Each can be considered as produced in a region approaching the observer at a certain velocity, ejected by a central object. Regions with the same expansion velocity not approaching the observer clearly contribute to the emission part of profiles.

During the development of a nova after its initial outburst, new absorption systems appear with generally increasing Doppler shifts and hence associated with regions having larger expansion velocities. The higher velocity regions tend to be more ionized, this being particularly true for the high velocity "Orion" absorption system, using the classical terminology of Mc Laughlin (1960). The velocity of each system need not be constant in time, that of the "Orion" system in particular can vary considerably. When the visual brightness of a nova has faded very roughly four magnitudes below maximum, the absorption systems disappear, the visual continuum tends to become faint, and nebular forbidden emission lines become strong. The nova has then entered the "nebular" stage when its physics can be more easily studied, and information concerning for instance the chemical composition of the ejected material be more easily obtained.

Certain other observations should also be emphasized. Firstly ultraviolet data especially have shown that the bolometric luminosity, though not quite constant as supposed by Gallagher and Code (1974), fades much less than the visual luminosity (Friedjung, 1977 ; Stickland et al., 1979). This is because the energy distribution shifts to shorter wavelengths after visual maximum. Secondly strong infrared excesses probably due to dust emission have now been observed for a number of novae several weeks after maximum (Bode and Evans, 1981). All novae do not show this, in particular it appears to be absent for very fast novae, and can only be strong for novae which fade between 0.04 and 0.08 magnitudes day^{-1} in the visual (Bode and Evans (1982)). The dust probably condenses in the ejected gas.

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Several types of simple model can be envisaged to explain the observations, and are described in my 1977 review (Friedjung, 1977a). All except one type of model involve the difference between instantaneous ejection (i.e. ejection in a time short compared with the time scale of development of a nova after the initial explosion) and continued ejection, two basic forms of each of these sorts of ejection being described. In fact even only using ground based observations, there is good evidence for continued ejection declining with time, though most mass (of the order of 10^{-4} $M_{\odot}$) seems to be ejected near visual maximum. The "principal" absorption system appears to be formed by material ejected nearly instantaneously not far from visual maximum, while the higher velocity systems are produced probably by a physically different process of continued ejection. As Mc Laughlin (1965) showed, higher velocities tend to occur nearer the ejecting object, and this is very important in elucidating the correct model.

Models involving only instantaneous ejection were popular for many years, as they are theoretically simpler. The balance of opinion has tended to go to the opposite extreme as a result of the discovery of the smallness of the decline in bolometric luminosity after visual maximum indicating continuing activity, this being found using ultraviolet observations. Also the interest in stellar winds since 15 years, has directed attention to the physics of continued ejection.

At this point I should mention some work about nova V 603 Aquilae 1918, that Professor Mustel has asked me to talk about. He has studied line profile changes during the quasi-periodic oscillations of the nova. He considers that the secondary maximum were due to thermonuclear mini-explosions which produced continued ejection at these times. A lack of spherical symmetry according to Professor Mustel is associated with the presence of a strong magnetic field.

The wind produced by a nova during continued ejection, is rather different from the winds of more "normal" stars. It seems to be optically very thick ; a photosphere is seen at a distance from the ejecting star above which the wind optical thickness is of order unity. The study of the continuous spectrum emitted by the photosphere gives direct information on the ejection rate. Most important of all there is strong evidence that the wind is supercritical, accelerated by the presence of radiation in the continuum of a central object above the Eddington limit. The acceleration of such a wind has been considered in several studies later than an early one of mine (Friedjung, 1966) : in particular those of Bath and Shaviv (1976), and Bath (1978) should be mentioned.

The reasons for believing the wind to be supercritical include especially the luminosities found using ultraviolet observations (Stickland et al., 1979 ; Friedjung, 1981). In addition extrapolation of the physical conditions in the photosphere to those below suggests ejection at a radius of the order of 10^{-2} that of the photosphere by radiation pressure. Also a comparison of the radiation flux to that of kinetic

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energy (Friedjung, 1981) is compatible with what one expects for a strongly supercritical wind. Finally theoretical calculations of thermonuclear runaways, suggest that a remnant with a luminosity not far from the Eddington limit, can be left after the initial explosion (Sparks et al., 1977 ; Sparks et al., 1978 ; Prialnik et al., 1978).

The physics of supercritical winds is not well understood; indeed one colleague once said to me that this sort of mechanism for novae is impossible. Consistent hydrodynamical solutions were obtained by Ruggles and Bath (1979). In solutions considered a substantial part of the luminosity is advected near the critical point at a great optical depth, so the proportion of the luminosity diffused outwards there is less than the Eddington limit. Conditions for such radiation trapped winds when the total luminosity is significantly above the Eddington limit, were suggested by me recently (Friedjung, 1981). An order of magnitude relation between the radiation and kinetic energy flux led to a very approximate formula, which in principle could partly explain the observed Orion system velocity variations. Expressed numerically this is :

$$\frac{L}{r_p} = 100\ V_s^3 \tag{1}$$

where L is the luminosity, r_p the photospheric radius and V_s the terminal wind velocity. Empirical comparison with the observations of FH Serpentis, suggest that

$$\frac{L}{r_p} = 10\ V_s^3 \tag{2}$$

is better. Several different types of supercritical wind with different conditions have even more recently been considered by Meir (1982). However many of his solutions are probably not relevant to novae.

Equation (2) can be used in an attempted interpretation of the very high velocity absorption components seen in the ultraviolet spectrum of nova Aquilae 1982. The absorption systems seen have velocities of about 3000 and 7000 km s^{-1}, and are present for strong lines in low resolution IUE spectra taken on February 24 and March 2 1982, this being clear from letters of T. Snidjders to the European IUE nova target of opportunity team (and also Snijders et al., 1982). The largest previously reported Orion absorption system velocity by Payne-Gasposchkin (1957) is 3820 km s^{-1}, and doubts have been raised as to whether nova Aquilae 1982 was a classical nova. However one sees from equation (2) that the system at 7000 km s^{-1} could have been produced in a supercritical wind if most radiation was emitted shortwards of Lyman α. The photosphere could then have had a radius of 1/2 x 10^{11} cm and a temperature of the order of 1 x $10^{5°}$. Whether this is the correct interpretation remains however to be seen.

Many problems concerning continued ejection in novae still remain

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to be solved. The interpretion of all the absorption systems is not clear ; in at least one case (V 476 Cygni) the large number of absorption systems makes one think of a large number of small clouds in the line of sight or even a form of turbulence. Collisions between parts of the envelope at different velocities can be expected, leading to X-ray emission detectable in later stages after the explosion, and playing an important role in the formation of new absorption systems. The effects of the stellar companion on the ejection process are not clear. Much more subtle analyses of the spectra of novae are necessary in order to deduce the physical parameters of different regions. It will be necessary to synthesize spectra, as considerable blending occurs between the broad complex profiles of different lines. The interpretation of the thermal radio emission of novae in terms of continued ejection models also is still not clear (Kwok, 1982). In any case there are still many difficulties in interpreting observations of novae which are both theoretical and observational. Many features of what should be the most suitable model are still uncertain.

c) Winds from old novae and also from other cataclysmic variables

Winds do not only occur from novae during their activity following an outburst. Ultraviolet observations with IUE show P Cygni profiles in the spectra of the old novae V 603 Aq., HR Del, and RR Pic, as well as in the spectra of a number of other cataclysmic variables such as dwarf novae in active states (Krautter et al., 1981 ; Klare et al., 1982, and other authors). These objects are considerably fainter than still active novae, and the winds must be of another nature. It appears that not only stars but also accretion disks are able to produce winds !

Mass loss rates have been determined assuming theoretical Castor and Lamers (1979) profiles by Krautter et al.(1981) ; Klare et al. (1982) and Cordova and Mason (1982) ; the last authors also compared profiles with theoretical profiles for doublets. Though doubts can be raised concerning the use of such profiles in the present situation, the fits are not bad for some cases at least. Cordova and Mason have attempted to correct for the probable conical shape of the wind. All these authors had trouble with the assumed ionization fractions, element abundances, and size of the base of the wind, so the derived mass loss rates are not very accurate. Rates of between 10^{-12} and 10^{-10} $M_\odot$ y^{-1} are obtained. The terminal velocities of the winds are up to 4000 km s^{-1}.

Cordova and Mason (1982) relate the observability of a wind to the orbital inclination of the binary system. This is used by them to support the concept of a conical wind, centered on the rotational axis of an accretion disk.

Making a small digression from the title of this talk, I shall mention the supergiant star S 22 in the large Magellanic cloud, which in a paper with Muratorio (Friedjung and Muratorio, 1980) was found to have a mass loss rate between 4×10^{-6} and 5×10^{-5} $M_\odot$ y^{-1}. More re-

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cent work has indicated that this may be a very young star surrounded by a gigantic short lived accretion disk, with an accretion rate of 10^{-3} to 10^{-2} $M_\odot$ y^{-1}. This star which may be unique in the Large Magellanic Cloud, could be another example of a wind from an accretion disk.

The nature of accretion disk winds is not more certain than that of those from more "normal" stars. Cordova and Mason (1982) point out that the wind momentum is of the same order as that of radiation for a dwarf nova during outburst. Hence radiation pressure in the lines might account for accretion disk winds, as in certain theories of "normal" hot star winds. I have tried very approximately to see whether the latest form of the line radiation pressure theory (Abbott, 1982) can predict the mass loss rate of the old nova HR Del. Remembering that different parts of a disk probably produce different winds, I took approximate values for the temperature, luminosity, and surface areas of that part of the disk from which radiation at 1500 Å, absorbed by the CIV P Cygni absorption profile, comes. A quarter of the minimum luminosity of Friedjung et al. (1982) was supposed to come from a disk photosphere at 40.000°. Taking a most probable primary mass of 0.9 $M_\odot$ (Bruch, 1982), a mass loss rate of 1.4 x 10^{-11} $M_\odot$ y^{-1} was predicted to be compared with the observed value of 2.6 x 10^{-11} $M_\odot$ y^{-1} found by Krautter et al. (1981) from the CIV profile. In view of the uncertainties including those involving the interpolation of the values of the constants of Abbott's theory, the agreement is far too good! Perhaps different sources of error cancel!

II. SUPERNOVAE

a) Types of star involved

It is not certain that similarity between novae and supernovae goes much beyond the fact that both types of star go bang and eject matter! A lot of especially theoretical work has been done on supernovae, which is beyond the scope of this talk. I shall only briefly touch on some aspects, including in particular the difficulties of interpreting the observations. Supernovae are interesting to many researchers because they appear to play a major role in nucleosynthesis, while their remnants have a major influence on the interstellar medium.

As is well known there are basically two types of supernovae, types I and II. Type I supernovae have very similar light curves and features in their spectra which are hard to identify, while type II have more variable light curves, and clearly identifiable lines with P Cygni profiles in their spectra, including especially Balmer lines. Type I supernovae are observed in all types of galaxy, while type II's are not observed in ellipticals. This was generally taken to indicate a difference of population ; type I supernovae were old population II stars, while type II's were young stars of population I. This point of view was supported by Maza and Van den Bergh (1976), who found that type II supernovae unlike those of type I were concentrated in the arms of spiral galaxies.

These ideas concerning the two types of supernova have been challenged in recent years. The statistics of Maza and Van den Bergh are uncertain according to Dennefeld (1982). Oemler and Tinsley (1979) considered both types of supernova to be produced in the evolution of massive stars, and hence belong to a young population. The reasons given by these authors are centered on the larger frequency of type I supernovae in galaxies with a young stellar population. If their arguments are correct, some young stars would have to exist in elliptical galaxies. This question goes beyond the subject of this talk ; all one can say is that it is very controversial at present.

Theoretical models of stars which become supernovae have been reviewed by Sugimoto and Nomoto (1980) (see also the references therein). Single stars of mass more than $4M_{\odot}$ can produce supernovae, and these authors distinguish what happens in different initial zero age main sequence mass ranges : 4-8 $M_{\odot}$, 8-12 $M_{\odot}$, 12-100 $M_{\odot}$, and more than 100 $M_{\odot}$. All these cases with hydrogen rich envelopes should give rise to type II supernovae ! Stars of such types should be either completely disrupted in the explosion, or give rise to a neutron star, or perhaps a black hole.

Type I supernovae if massive single stars would have a mass near 9 $M_{\odot}$ according to Weaver et al. (1980). Slightly more and slightly less massive stars would not have the required characteristics according to these authors. Maeder (1981) considers that type I supernovae might be produced by stars with initial masses above 30 $M_{\odot}$, but does not prove that this process would lead to a type I supernova.

If type I supernovae are old low mass stars, they could be accreting white dwarfs in close binaries. Various cases are mentioned by Sugimoto and Nomoto, and it appears that if all the accreted gas is not ejected in milder classical nova explosions, a supernova can be produced. In this case type I supernovae at least are closely related to classical novae. Recently Nomoto (1982a,b) has calculated models of carbon-oxygen white dwarfs accreting helium, which for instance could be the result of the burning of accreted hydrogen including in nova explosions (see also Fujimoto and Taam, 1982). The results are sensitive to the accretion rate of gas on to the white dwarf.

b) Interpretation of supernova observations

Observations of supernovae are both of poorer quality, and harder to interpret than those of classical novae after their outbursts. A basic difficulty is that spectral line profiles are considerably broader, corresponding to ejection velocities of the order of 10^4 km s^{-1}, so much blending occurs. Now spectra need to be analysed for a correct model to be found ; one cannot base everything on light curves!

Most of the large amount of interpretation of supernova spectra during the last decade has been based on the idea that one sees mainly lines of low states of ionization (in particular singly ionized metals). A photosphere emits a strong continuous spectrum, and the P Cygni absorption components deserve particular study. These ideas have been particularly developed by Branch, Mustel and their co-workers.

The basic model is one of instantaneous ejection of an envelope with a velocity gradient, so the fastest moving material is at the outside furthest from the ejecting star (called instantaneous ejection type II in my discussion of classical nova models (Friedjung, 1977). The inner part can be optically thick in the continuous spectrum for a time and a photosphere occur near an optimal depth of unity. Chugai (1975) found from the time variation of the wavelengths of features identified as P Cygni absorption components, that the inner regions of type II envelopes had higher densities and lower velocities (and hence Doppler shifts) than the outer regions. On the other hand the unchanging wavelengths of similar features of type I supernovae led Chugai to conclude that their absorption components were formed in a density maximum, which means a shell of greater density seemed to exist which could be well separated from the photosphere. Branch (1977) studying type I supernovae within 20 days of maximum light found indications of a large density gradient in the places where the photosphere was supposed to be situated at that early epoch.

Important results have been obtained from ultraviolet observations with IUE. Panagia et al. (1980) investigated the type II supernova 1979c. The conclusions of that paper have had to be revised, and the deductions that can be made from the observations of several supernovae by IUE were given by Panagia (1982). A UV excess in the two type II supernovae studied can be explained by two photon emission from the upper layers of the ejecta. Interstellar absorption distorts the emission line profiles, and led to an underestimate of widths in the first paper. The UV emission lines of highly ionized species seem to have little or no blueshifted absorption. In the case of the supernova 1979c (they were formed between 1 and 1.3 photospheric radii, in a region with an electron density between 10^9 and 10^{10} cm^{-3} during late April 1979. The mass of the emitting material was about 0.2 $M_\odot$, and the abundance ratio N/C in the region emitting these lines about 30 times the cosmic value. Some lines, in particular NIII] 1750 Å had a narrow component with a Doppler width less than 10^3 km s^{-1}, probably due to the pre-existing wind of a red giant progenitor. This fossil wind was also thought to produce freefree absorption of the radio emission this being used to calculate its mass loss rate of about 10^{-5} $M_\odot$ y^{-1}.

The situation as far as the interpretation is concerned, is much worse for type I supernova observations. Panagia (1982) suggested that there is an excess in the optical region as compared both with the ultraviolet and with the infrared. The optical excess would be due to emission lines much stronger than the continuum, and this would contradict the Mustel and Branch spectrum interpretation for this type of supernova. In view of the attractive simplicity of the interpretation, I expect Panagia's suggestion to be resisted vigourously !

In any case the optical spectrum of type I supernovae presents problems. It is still not sure whether Hα is present. I tried in a paper once (Friedjung, 1975) to prove its existence, but the majority opinion seems to be against. Indeed I found the subject not attractive because it is difficult to prove anything at all ! However some important work has been done in recent years in the interpretation of both spectra and light curves, considering the presence of a radioactive energy source. The source could be $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$. Meyerott (1980b) has synthesized spectra taking the FeII and FeIII lines. The radioactivity ionizes and the model can also be used to determine a mass of the ejected envelope of about 1 $M_\odot$ if the ejection velocity is 10^4 km s^{-1}. The atoms other than iron are supposed to have an atomic weight of 28. It should be pointed out (Meyerott, 1980a) that this type of model leads one to expect type I supernovae not to have continua after luminosity maximum, perhaps supporting the conclusion of Panagia (1982). Another similar type of model is described by Axelrod (1980).

IV. CONCLUSIONS

Processes of mass loss, different from those of calmer stars have been examined. Explosive mass loss occurs in novae and supernovae, and winds play an important role in novae. Novae after their explosions probably have supercritical winds, coming from a star which can be significantly above the Eddington limit. There may not exist many other sorts of object with the required extreme conditions. On the other hand winds of old novae and other cataclysmic variables with mass loss rates of about 10^{-6} times less, though coming from accretion disks, may not differ radically from winds produced by "normal" hot stars.

Observations outside the optical range and especially in the UV have played a fundamental role in the obtaining of these results. Far more of this kind of observation is needed. In particular it is important to study the region below Lyman α, and it is to be hoped that plans for satellites able to do this will be successful.

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