THE CLASSIFICATION OF SUPERNOVAE

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Abstract. The present status of the Minkowski–Zwicky supernova classification is reviewed. Some very recent theoretical and observational results are mentioned, and their direct impact in our knowledge of the physics of supernovae and their classification are discussed. We also examine the possibility of imagine an alternative based taxonomy for supernovae, derived mainly from what we know about the physical processes involved in those stars, trying to correlate these physical types to the observational evidences available, in order to see if such a scheme would be useful, in practical terms.

1. Introduction

The first extragalactic supernova was observed on August 31, 1885, near the nucleus of NGC 224 (M 31). Later, Minkowski (1941) concluded that there were 'at least two types of supernovae', based on a total sample of 14 objects. The first group, 'provisionally' called 'type I' was extremely homogeneous, and did not show hydrogen lines in their optical spectra. The second one was a very heterogeneous class, but all objects exhibited Balmer lines. This group was designated 'provisionally' as 'type II' by Minkowski.

The supernovae classification has evolved since then. Zwicky (1964a, 1965) has proposed an extension to the original scheme, introducing his types III, IV, and V. All of them were stars with H lines.

The photometric differentiation of type I into 'I fast' and 'I slow' was proposed by Barbon *et al.* (1973), but has remained unconfirmed up to date. At least two spectroscopic subtypes of type I supernovae have been dramatically established in recent years: namely, the types Ia and Ib which respectively show and do not show the Si II λ6150 Å absorption feature in their spectra (e.g., Porter and Filippenko, 1987). Such a difference had been pointed out in earlier papers by Bertola (1964) and Bertola *et al.* (1965).

There has also been a proposal of dividing type I supernovae into two subgroups, classified as to their probable progenitors. Dallaporta (1973) suggested that supernovae 'I young' (Iy) originate from young and massive stars, while 'I old' (Io) supernovae come from old and less massive stellar populations. Such a conclusion has been supported by other studies (e.g., Oemler and Tinsley, 1979).

Type II supernovae were divided into two photometric subtypes by Barbon *et al.* (1979), according to the presence (II-P) or absence (II-L) of a 'plateau' in the descending branches of the visual and photographic light curves of those objects. More recently, we suggested that those supernovae such as SN 1987A in the Large Magellanic Cloud were a third photometric subtype, designated as II-B, or 'II Bump' (da Silva, 1990a, b), because of their 'ascending plateaus' in the light curves, which give them a peculiar

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shape. A spectroscopic differentiation in nature has also been proposed for type II supernovae by Filippenko (1988a). He suggested to divide type II into IIa and IIb supernovae, in analogy to type I. Another new tentative spectroscopic subclass of type II supernovae was also proposed by Schlegel (1990): namely, the IIn (n for 'narrow' lines presented in optical spectra).

Pskovskii (1977a, b, 1978) introduced the concept of photometric class to measure the velocity of the light curves of both main types of supernovae, and studied its relations with physical parameters of the stars. Some of his relations are still controversial.

Finally, an alternative scheme for sorting out supernovae has been proposed by Harkness and Wheeler (1990), considering their behaviour during maximum light and about six months later.

In this paper, we briefly review the present status of the current Minkowski–Zwicky (MZ) classification for supernovae in order to see if it could accommodate several observational and theoretical results obtained in the last ten years or so. In Section 2 we summarize the theoretical models proposed for supernovae up to date as well as the results from some recent works which may have a major importance to the subject. Section 3 deals with several peculiar objects related to the supernovae. Section 4 contains a discussion of the main points included in the text, before mentioning the old physical classification proposed by Shklovskii (1982, 1983) and then, in the following sections, we try to suggest an alternative modern scheme. The last section presents the main conclusions of this work.

2. Theoretical Models and Observations

In this section we will summarize the main ideas and models which have been proposed in the literature in recent years, as well as, some recent important observational results.

2.1. Type Ia supernovae

In spite of some older models as those by Lasher (1975) who suggested the hydrodynamic explosion of stellar cores, or Ostriker and Gunn (1969) who speculated about pulsar related explosions, theoretical models for type I supernovae have shown little variations around the same basic aspect: the explosion of a white dwarf.

Hoyle and Fowler (1960) pointed out this possibility, but the modern 'standard models' are generally considered as being derived from one proposed by Whelan and Iben (1973). In this version, it is assumed that a white dwarf with a degenerate CO nucleus accretes matter from a nearby companion. The mass accretion induces the elevation of the core temperature and density so that, once the Chandrasekhar's limit is attained, the nuclear off center runaway reactions become more important than the energy losses via neutrinos. The star is totally anihillated, but we can distinguish two main possibilities according to the velocity propagation of the burning front inside of the star. The first one is a subsonic burning (called a deflagration), while the second case involves a supersonic propagation (a detonation). A deflagrating model has been calculated by Nomoto *et al.* (1986), and it is in good agreement with the optical spectra of the well-observed type I supernovae. The main problem of the detonating models (e.g., Woosley *et al.*, 1986) is that they predict a very high iron abundance, and a small quantity of the mean mass elements synthetized during the explosion. Nevertheless, helium detonating white dwarfs have been invoked to explain some peculiar type I supernovae with fast light curves, such as the case of the poorly observed SN 1885A (S Andromedae; see, e.g., Chevalier and Plait, 1988). It seems that deflagrating type I supernovae are much more common in the Universe than the detonating ones, but it is also possible that detonating supernovae are affected by some type of selection effect (for example, one derived from their faster light curves), or even that detonations do not occur in nature.

It is also worth observing that a large variety of evolutionary scenarios as well as slightly alternative models ending in a type I supernova have been proposed in the literature. The final point of most of them is an exploding white dwarf. See, for example, Wheeler (1978), Nadezhin and Utrobin (1976), Webbink (1984), Iben and Tutukov (1984), Warner (1974), Arnett (1979), Lopez *et al.* (1986a, b), Graham (1987), and Hachisu *et al.* (1989), among others. Probably there are several possible ways to obtain a pre-type I supernovae configuration.

2.2. Type Ib supernovae

The first examples of this subclass were discussed by Bertola (1964) and Bertola *et al.* (1965). However, the subject has risen relatively little attention up to recently, particularly after the work by Elias *et al.* (1985) who pointed out the existence of peculiarities in the infrared light curves of some type I supernovae. Also the papers by Wheeler and Levreault (1985) and Filippenko and Sargent (1986) which deal with the spectroscopic anomalous type I SN 1983N and 1984L, and 1985F, respectively, were important. Several of these supernovae have been discovered in recent years, suggesting they may be common in the Universe.

From a spectroscopic point of view the now called type Ib supernovae do not show hydrogen lines. During maximum, the spectral appearance is that of a type Ia supernova one or two months past maximum. Apparently one of the most effective tests distinguishing a type Ib event is the absence of the deep absorption at λ6150 Å, attributed to Si II. This feature is very conspicuous in Ia supernovae during the first 25 days past maximum light. Porter and Filippenko (1987) summarized the general properties of type Ib events, as a consistent subclass of supernovae.

There is a large variety of theoretical models which have been invoked to explain type Ib supernovae. Some of them are variations of the basic scenario accepted for type Ia, such as those suggested by Branch and Nomoto (1986) and Khokhlov and Ergma (1986). These models assume off-center detonations in white dwarfs. Other models include hydrogen deficient binaries (Uomoto, 1986), core collapses of massive stars stripped of their hydrogenated envelopes (Wheeler and Harkness, 1987), and core collapses in Wolf–Rayet stars (e.g., Begelman and Sarazin, 1986; Filippenko and Sargent, 1986; Gaskell *et al.*, 1986).

It is important to mention that there are several observed heterogeneities between members of type Ib supernovae, such as variations in the helium, carbon, and oxygen abundances (Wheeler *et al.*, 1987), and even the presence of some shallow hydrogen P-Cygni profiles (Filippenko, 1988b). Also some Ib supernovae seem to produce very large amounts of oxygen (Begelman and Sarazin, 1986). These intrinsic dispersion in physical properties may indicate that type Ib supernovae *are not* produced by a single class of progenitor stars. Configurations as Wolf–Rayet stars and massive stars which have lost their hydrogen envelopes may be involved. Such a possibility has been emphasized by Filippenko (1988a).

2.3. Type Ic supernovae?

Wheeler and Harkness (1986) suggested that type Ib SN 1983V in NGC 1365 could represent a third subtype of type I supernovae, which was called by them as 'Ic'. The reason was that, in addition to the absence of λ6150 Å absorption feature, the strong line in λ5700 Å (proeminent in supernovae Ib 1983N and 1984L) was not visible. However, it seems to us that this is not a sufficient argument to determine a possible new class of supernovae. It makes sense, instead, to assume an intrinsic heterogeneity of type Ib subclass, perhaps associated with changes in the environmental properties of each explosion, or with different types of progenitor stars. Nevertheless, Wheeler and Harkness (1990) have apparently confirmed the existence of type Ic supernovae.

2.4. 'Pecular' type I supernovae

Notation 'I peculiar', or simply 'I pec' was used by some authors when it still was not well established the existence of type Ib supernovae as a subclass. However, Branch (1986) used that expression with a different meaning, to isolate those type I supernovae which were not typical of, neither Ia nor Ib subtypes, showing 'individual peculiarities'. He indicated five cases: SNs 1885A, 1954A, 1957A, 1980I, and 1983V. SN 1885A and also SN 1957A did have fast light curves. SN 1954A is uncertain because it was poorly observed. SN 1983V is now considered as a type Ib event, while SN 1980I was only 'slightly peculiar', showing an unusual absorption feature near λ6680 Å. The deep at λ6150 Å was present, so that it could be classified as a type Ia object.

In summary, supernovae 'I pec' not classified as Ia, Ib, or even Ic should be taken as additional evidence that real physical discrepancies did occur in those subtypes.

2.5. Type II supernovae

Type II supernovae have been considered as a very heterogeneous group since the work by Minkowski (1941). On the other hand, it is rather surprising that all of them have been attributed to the hydrodynamic core collapses of massive stars (usually considered to be red supergiants). The reader should compare this 'uniformity' in type II models with the confuse situation which characterized the models for type I supernovae during, e.g., the 1970's.

Collapsing models have been calculated by many authors. Arnett (1971) and also

Falk and Arnett (1973) considered the shock wave propagation in the envelopes of exploding stars where the radiative transport was by photon diffusion. Their models reproduced quite well the observed light curves for type II supernovae (e.g., Arnett and Falk, 1976).

There have been small variations in the basic physical scenario. For example, Grasberg and Nadezhin (1986) constructed a model in which two explosions occurred. Also Zentsova (1976) speculated about a totally different model: the explosion would be ignited by rotational kinetic energy conversion from the nucleus of a red supergiant into shock wave energy which would eject the star's envelope.

Among the principal limitations of the traditional collapsing models one can enumerate:

(1) The assumption of a spherically-symmetric explosion (Shapiro and Sutherland, 1982). There is no direct observational evidences for such a situation. On the contrary, recently Karovska *et al.* (1988) detected asymmetries in the expanding envelope of SN 1987A. Factors which may create deviations from a spherically-symmetric explosion are fast rotation, magnetic fields, the presence of a companion in a binary system, etc. Non-spherical explosions may affect the emission of gravitational waves (Saens and Shapiro, 1981), and the use of supernovae as distance indicators (Wagoner, 1979).

(2) The models are generally 'one-dimensional'. They take into account only the thermonuclear, or gravitational aspect of a supernova. A two-dimensional model has been calculated by Bodenheimer and Woosley (1983).

(3) The weak coupling between the core collapse and the envelope ejection, due to the fast damping of the shock wave emerging from the core bounce. Several authors have proposed solutions for this problem, invoking the concept of a neutrinosphere (Freedman *et al.*, 1977).

Most traditional models assume the core collapse of a red supergiant with solar metallic abundances, originating a neutron star or, perhaps, a black hole (in the most extreme cases); However, SN 1987A introduced some new unexpected facts, as we shall see in Section 3. A neutrino pulse corresponding to the intense neutronization reactions in the collapsing core is emitted, and has been dramatically confirmed in the case of SN 1987A (e.g., Hirata *et al.*, 1987; Svoboda, 1987; Alexeyev *et al.*, 1987; and possibly Aglietta *et al.*, 1987).

3. Peculiar Objects

There are several objects possibly or directly related to supernovae and their remnants, which show peculiar properties or uncommon behaviour. We will briefly discuss Cas A, η Carinae, the SN 1961V in NGC 1058, SN 1987A, and a class of supernova remnants (SNR) rich in nitrogen and oxygen, although others could be also included.

3.1. Cassiopeia A

This object is a young supernova remnant located near the galactic plane and it is the strongest radio source in the sky at metric wavelengths ($=$G111.7 $-$ 2.1). Baade and

Minkowski (1954) associated Cas A with a fast expanding optical nebula with knots and filaments. Kamper and van den Bergh (1976) estimated 1657 as the probable year of the explosion, so it is surprising that there is no known record of the visual supernova, suggesting a faint event. If Cas A had been a typical supernova and taking into account the effect of the interstellar absorption, van den Bergh and Dodd (1970) calculated a peak magnitude equal to + 2. If one adopt a mean absolute magnitude of − 19 to the Ia supernovae, and − 17 for Ib and type II events, and if the distance of 2.8 kpc (van den Bergh and Dodd, 1970) is correct, then using the cossecant law for galactic absorption, it is found that, if Cas A was a type Ia explosion, it would have shown a maximum visual magnitude of about + 0.4. In the case of a Ib or a II event, this value diminishes to + 2.4. On the other hand, using the value $A\nu = 4.3$ given by Searle (1971), those numbers would be even more extreme: − 2.5 and − 0.5, respectively. Using the larger distance obtained by Clarck and Caswell (1976), i.e., 3.3 kpc, the results would be 0.8 and 2.8 (cossecant law), or − 2.1 and − 0.1 ($A\nu = 4.3$). Such a star would be easily seen, because in that period at least two ordinary novae were seen from Europe: 1667 (V 529 Orionis), and 1670 (CK Vulpeculae), according to Pskovskii (1972). We, therefore, assume that an object brighter than $m_v = +3$ would be noted, so it is possible to estimate an upper limit for the maximum probable absolute magnitude of Cas A. Assuming $d = 2.8$ kpc, this absolute visual brightness would be − 16.4 (cossecant law) or − 13.5 (if $A\nu = 4.3$). On the other hand, if $d = 3.3$ kpc, these corresponding results would be − 16.8 or − 13.9. All of them indicate a considerable subluminosity.

The independent suggestions by Brosche (1967) and Chu (1968) relating Cas A to the star registered in Corea in the year 1592, although rather interesting as to the position, are incompatible with the estimated age of the remnant. Thus, we conclude that Cas A was intrinsically subluminous, although Flamsteed may have seen the star (cf. Ashworth, 1980; also Kamper, 1980).

Given its youth this remnant is still in its initial phase of free expansion. The interaction with the interstellar medium may be neglected, and as a consequence we can learn a lot of things about the nature of the progenitor star, by analysing the SNR's dynamics, its structure and chemical composition stratification. Contini (1987) found Cas A to be consistent with the explosion of a WN star. Such a configuration would produce a subluminous supernova (see, e.g., Chevalier, 1976) with a narrow peak of light. It is, moreover, totally different from a red supergiant.

There is no bound remnant known for Cas A (Helfand and Becker, 1984; van den Bergh and Pritchet, 1986). A black hole has been suggested by Shklovskii (1979), but Brecher and Wasserman (1980) pointed out that there could be no compact remnant at all. This is consistent with the explosive oxygen burning simultaneous to the core collapse (Stringfellow and Woosley, 1988).

So, the general conclusion seems to be that Cas A was some different type of supernova, probably derived from a WR or a nitrogen-rich OB star. This enlarges the collection of possible progenitors to the collapsing supernovae.

3.2. η CARINAE

The nature of this object is controversial. It is a massive very luminous star which is part of an O3 association. The brightness has varied randomly and, in 1843, a maximum of $m_v = -1$ was observed. The magnitude dropped considerably since then due to the dust condensation. Feinstein *et al.* (1973) estimated a probable age of a few times 10^6 years of the related OB associations in this region of the sky. The η Carinae's bolometric magnitude has been constant and equal to -11, even after the main 1843 maximum. The probable distance is 2.5 kpc (Thé *et al.*, 1980) and Andriesse *et al.* (1978) obtained a mass loss rate of 0.075 $M_\odot$ yr^{-1} which is several orders of magnitude larger than those ordinarily found in Wolf–Rayet stars.

There is no doubt that η Carinae is a very massive short-lived object. However, its true evolutionary status is not well known. Moreover, Weigelt and Ebersberger (1986) showed that η Carinae is not a single object, but a compact cluster of 4 stars, forming a supermassive and probably unstable trapezium. Davidson and Humphreys (1986) adopted initial masses of 100, 65, 65, and 65 $M_\odot$ for the components.

η Carinae is a rare type of object, but it is certainly not unique. The scarseness of objects like it is probably due to the fact that very massive stars are rare and evolve fastly. Another example of this class of objects may be variable 'A' in NGC 598 (M 33), according to the work by Humphreys *et al.* (1987). Some relation with the Hubble–Sandage variables can also be possible.

We consider η Carinae as an extremely massive group of Main-Sequence stars where each component evolves independently. If one adopt the mass suggested by Davidson and Humphreys (1986), then it is possible that the most massive one may be already experiencing a Wolf–Rayet phase. This could explain the observed presence of nitrogen (cf. Davidson *et al.*, 1982). These very massive stars are frequently erratic variables, so it may be that the observed variations in brightness are the result of characteristic instabilities which are presumably occurring in the four stars simultaneously. Possibly the most massive component may have been the main responsible for the 1843 maximum. So, the extreme behaviour of η Carinae is not related to the supernovae as discussed in the previous section, and Zwicky's inclusion of it in his 'type V' (Zwicky, 1964b) is not reasonable today. Apparently η Carinae is more closely related to the luminous blue variables (LBVs) than to the supernovae properly said. We will return to this point later in this paper.

3.3. THE 'PECULIAR' SUPERNOVA 1961V IN NGC 1058

This object is the prototype of 'type V' supernovae proposed by Zwicky (1964a, 1965). It was discovered by Wild (1961) in the outskirsts of the spiral galaxy NGC 1058. The light curve and the spectrum were dissimilar of normal supernovae, and the maximum occurred in December 1961 with an absolute photographic magnitude -18. Extensive reviews of the behaviour of this unusual object may be found in the analysis by Bertola (1963) and Utrobin (1984). The progenitor star was visible in old plates, taken in 1937 (with $M_{ph} = -12.7$).

Several interpretations were suggested to explain SN 1961V. The first one was proposed by Zwicky (1964b) and considered SN 1961V as an η Carinae-like object. Branch and Greenstein (1971) conserved this relation but argued that it could be explained as an intermediary class between classical novae and normal supernovae, calling SN 1961V a 'slow supernova'.

Utrobin (1984) developped an entirely new interpretation. According to him, SN 1961V derived from the explosion of a super (or hiper?) massive star with a ZAMS mass equal to 2000 $M_\odot$ and a radius $R = 100\ R_\odot$. More recently, Goodrich *et al.* (1989) criticized Utrobin's theory and proposed to explain SN 1961V not as a supernova but as a super explosion of a luminous blue variable (LBV) with probable initial mass around 240 $M_\odot$. Thus, the original idea by Zwicky (1964b) has been recovered, and now it seems probable that SN 1961V was a 'pseudo-supernova', and that η Carinae explosion in 1843 could be a smaller version of this class of objects. It is also worth mentioning the work by Humphreys and Aaronson (1987) according to which the distant very luminous extragalactic 'stars' are not always single objects, being frequently compact clusters of bright blue supergiants. Therefore, it is possible that the object seen at least since 1937 in the parent galaxy NGC 1058 was a multiple star, or a small group of stars. In fact, its high absolute magnitude before explosion suggests this could be the case.

3.4. Supernova 1987A

Supernova 1987A was a peculiar object because:

(1) The morphologies of the light and colour curves are very unusual. Relations of SN 1987A with rare objects such as SN 1961V or Cas A (Menzies, 1987) do not seem consistent today. Also the suggestion by Cristiani (1987) that there could be a continuous transition of properties from II-L supernovae like the well-observed SN 1979C and the typical II-P ones (e.g., SN 1980K) being SN 1987A an extreme case in that sequence may be discussed.

(2) SN 1987A was subluminous at maximum ($M_B = -16.04 \pm 0.01$; $M_V = -15.26 \pm 0.06$; see da Silva, 1990a; also Hamuy *et al.*, 1988; Menzies *et al.*, 1987, Catchpole *et al.*, 1987a,b; Dopita *et al.*, 1988). This was due to the conversion of a part of the explosion energy into kinetical energy which was used to expand the star's envelope.

(3) The initial spectral evolution was anomalously fast. For example, the infrared triplet of Ca II at λ8600 Å was visible only 4 days after the discovery.

(4) The initial velocity extrapolated to Hα line (-18000 km s^{-1} on February 25, 1987 – Blanco *et al.*, 1987) was not equaled by any well-observed type II supernova.

(5) The progenitor star was a blue supergiant (Sk – 69°202), and not a red one, as suggested by the canonical models.

(6) The early ultraviolet spectra were reminescent of a type Ib supernova.

(7) The primordial ultraviolet flux decayed very fast, indicating a considerable cooling of the photosphere.

(8) The X-ray and UV early emission in ordinary type II supernovae are probably

resultant of the propagation of the shock wave in the extended rarefied envelope of a red supergiant. But Sk – 69°202 did not have such an envelope, so its emission must be due to an entirely different mechanism (McCray *et al.*, 1987).

(9) There was sudden radio detection, different of the common type II supernovae (cf. Manchester, 1987). The nature of the radioemission was probably non-thermal.

These are just some points distinguishing SN 1987A from the vast majority of the other well-observed supernovae. It is possible that some other poorly observed objects may be like SN 1987A. Between them we have SN 1909A (Milone *et al.*, 1988), and SN 1990H in NGC 3294 (Filippenko, 1990). Probably these objects may be explained based on their low metallicity, and we have suggested to consider them as an isolated subclass called 'II Bump', based on their light *B* and *V* curves (see da Silva, 1990a, b).

Supernova 1987A has increased the family of probable progenitors for collapsing supernovae. Today we can speak at least of Wolf–Rayet stars, red supergiants, and low metallicity blue supergiants. And there may be other types of stars producing supernovae via core collapsing mechanism.

3.5. Supernova remnants with anomalous abundances

There is a class of supernova remnants (SNRs) which show unusual enrichments of nitrogen and oxygen. They are certainly related to massive stars explosions, and some of them are like the galactic SNR Cas A. Several of these SNRs can be found in the Large Magellanic Cloud (LMC). For example, Lasker (1978) published an analysis of the LMC SNR N132D, which shows fast moving knots and intense emission of O II (λ3727 Å) and [O III] λ4959, 5007 Å). The age of this remnant is controversal. Westerlund and Mathewson (1966) determined it as 300 years, while Danziger and Dennefeld (1976) found 3000 years.

Another LMC SNR of this type is 0540–69.3 (Mathewson *et al.*, 1980), showing a [O III] $\lambda 5007/H\alpha$ ratio larger than 60. There is also a pulsar related to this remnant, according to Seward *et al.* (1984), so it seems obvious that it was produced by a collapsing supernova event.

A third example, pertaining to the Galaxy, is MSH 11–54 (Murdin and Clark, 1979). These objects seem to have a toroidal structure (but see Shaver, 1982). Market *et al.* (1981) pointed out such a feature for Cas A too. Supernova remnants with toroidal-like symmetries are suggested by two dimensional models for core collapse which include nuclear burning and rotation (Bodenheimer and Woosley, 1983).

There are seven SNRs with enrichments of oxygen known today, four being associated with H II regions. So it seems certain that these objects are indeed produced by explosions of very massive stars. Probable progenitors could include OB and Wolf–Rayet stars.

Van den Bergh (1988) proposed a 'highly tentative correlation' between the main spectroscopic types of supernovae and the three commonest types of observed SNRs. According to his scheme, type Ia supernovae derive from white dwarfs, producing collisionless shock remnants. Blue (O) and WR stars would be the possible progenitors of type Ib supernovae, originating oxygen-rich SNRs, while B stars would be responsible for type II supernovae, and the plerionic remnants as the Crab nebula.

We suggest that O-rich SNRs can result from massive stars explosions (O, WR, and even B stars). There is no proof that all Ib supernovae produce this type of SNR and, if different classes of progenitor stars effectively originate Ib explosions, then there is no reason to believe all would do it. Moreover, plerions can be probably derived from red supergiants too, and this possibly was the case for Crab nebula.

In all cases, rich O, N, SNRs are important to show that there are various types of progenitor stars producing collapsing supernovae, and some of the possible configurations involved are not hydrogenated, so that the traditional MZ classification may encounter no serious problems.

4. Discussion

The point is that today we can construct a tentative physical general view about supernovae phenomena, which was totally impossible just ten years ago. Our knowledge had advanced to the limit as to admit several progenitor configurations, different explosion mechanisms, and also to consider the influences of the immediate interstellar medium on the supernovae, as well as, the importance of the physical structure of the star's envelope in the conditioning of the spectroscopic and photometric display in a supernova.

Here we will try to summarize some of the points we judge important and which have been made available in recent years, concerning to theoretical and observational studies of supernova. Then, we will comment on the capability of the usual MZ classification in accomodating them.

We would like to enumerate the following points:

(1) Supernovae phenomenology is probably much more diversified than previously suspected.

(2) The most accepted physical scenario for type Ia supernovae is that of a CO deflagrating white dwarf, in a binary system with mass capture. Detonations seem to be very rare, but they cannot be totally excluded yet. If detonations are common in nature, then some observational selection effect may be impeding us to observe them. Such an effect could be related to the very fast light curves presented by detonating supernovae as inferred from theoretical models. There is also probably several evolutionary paths which may end on a type Ia supernova.

(3) There are real physical inhomogeneities between type Ia supernovae, and these may be caused by different environmental properties, differences in explosion mechanisms (such as carbon deflagrations, helium detonations, mono or double detonations, etc.), rates of mass capture, etc.

(4) Type Ib supernovae may be associated with the general phenomenon provocating the ordinary type II supernovae. Again, we have important real discrepancies between type Ib explosions (see, e.g., Filippenko and Sargent, 1986; and Filippenko, 1988a). It is even possible that several very different stellar configurations as Wolf–Rayet stars

and normal massive (10–20 $M_{\odot}$) stars deprived of their hydrogen envelopes are producing type Ib supernovae.

(5) The traditional 'heterogeneity' of type II supernovae must be considered as a real indicator that very different progenitor stars are effectively involved.

(6) The photometric classification by Pskovskii must be revised, because it does not consider the difference between types Ia and Ib and, furthermore, any correlation between his parameter β with different physical types of supernovae remains obscure, having not been investigated in detail. It may even be that such a possible relation is not exclusive.

(7) There is at least two entirely different classes of phenomena which we are generically designating as 'supernovae'. Both have no major relations between them, excepting some coincidental effects such as a similar energetics, nucleosynthesis, and the presence of late radioactive decays. Obviously, the existence of these two basic types of phenomena and the two spectroscopic original types in the MZ classification is only a coincidence.

(8) Objects as Cassiopeia A are strong evidences that Wolf–Rayet stars may be exploding by core collapses. These are not hydrogenated stars, so they would produce 'type I supernovae', some of them we can be observing as type Ib explosions. That is, the presence or absence of hydrogen lines in a supernova optical spectrum says almost nothing about the mechanism disparating the explosion. We may have core collapse supernovae with and without hydrogen in their envelopes, and may even imagine the opposite, i.e., a moderately massive carbon deflagrating supernova which have a hydrogen envelope. This would be a speculative 'type I1/2' supernova, as proposed by Iben and Renzine (1983).

(9) Zwicky's type V supernovae probably are not 'authentic' supernova explosions. They are related to instabilities which occur in very massive young stars, a family designated as 'luminous blue variables'. η Carinae is an example of this type of objects. Their better known extragalactic counterpart is represented by SN 1961V.

(10) The very few known examples of Zwicky's types III and IV do not seem to show extreme peculiarities as to be distinguished as different types of explosions. They may be well considered as somewhat peculiar type II explosions.

(11) The observational difference between type II supernovae found by Barbon *et al.* (1979): namely, II-P and II-L, is certainly valid, and may be perhaps understood in terms of the mass losses of the progenitor stars. Supernovae of type II-L possibly originate from more massive stars which experienced a higher mass loss than those which produce the more common II-P explosions. However, II-L and II-P do not represent the totality of the light curves morphologies which are possible to type II supernovae. Supernova 1987A is a dramatic example of this. Types II-L and II-P can be only the commonest occurring in nature.

(12) Supernova 1987A demonstrated the importance of the metallicity on the evolution of massive stars. This question *is not* taken into account in the MZ classification. It also shows another aspect: the physical nature of the star's envelope is a major determinant of the photometric and spectroscopic evolution of a supernova, although

phenomena such as neutrino pulses, which happen very deep inside the star, in the nuclear region, do not seem to be so sensitive: the neutrinos behaviour of SN 1987A was a very 'canonical' one, but not so its visual properties! Then, it is fundamental to consider the physical nature of a progenitor supernova star, and this have profound consequences to the MZ classification scheme.

(13) We can imagine today several types of progenitors of collapsing supernovae: red supergiants, blue supergiants, perhaps yellow supergiants (see Maeder, 1987), WR stars, very massive stars (e.g., Stringfellow and Woosley, 1988), etc. Although the question may be complex, there is apparently some limit on mass, perhaps about $40 \pm 20\ M_{\odot}$ above which a solar metallicity star never experiences a red supergiant phase, not producing a canonical type II explosion (see Doom *et al.*, 1986). A more precise definition of a 'canonical' type II supernova will be given in Section 7.

Now one can realise the troublesome situation of the old classification for supernovae we are used to employ. This classification was basically introduced as a preliminary one, and has been used during 50 years! It is certainly not physical enough today, and this is a serious problem if one is studying the rôle of supernovae in the metallic interstellar medium enrichment (e.g., Matteucci and Greggio, 1986), or the use of supernovae as distance indicators. It also affects the supernovae rates (e.g., Bartunov *et al.*, 1991);

In the following sections we will discuss an alternative classification scheme, which could more adequately discern physical aspects concerning to the supernovae explosions and their evolution.

5. The Shklovskii's Physical Classification for Supernovae

It seems that Shklovskii (1982) was the first to call attention to the physical deficiency of the usual MZ classification. He proposed an alternative scheme comprising four physical types of explosions.

The first type was a star which experienced a non-degenerate core collapse, surrounded by a hydrogen envelope. These events would generate the canonical type II supernovae, and their pre-explosion configuration would correspond to an ordinary red supergiant.

Type I supernovae would be produced by the degenerate core collapses occurring in stars deprived from their hydrogen atmospheres.

He also imagined two additional types: namely, the non-degenerate core collapse in a star whose hydrogen envelope had been lost by mass transfer to a secondary in a binary system, and the degenerate core collapse with a hydrogen envelope, which would correspond to a low mass red giant producing a ^{56}Ni core, which resulted totally annihilated by the supernova explosion.

In a subsequent paper, Shklovskii (1983) speculated about three possible evolutionary ways which could produce a supernova, calling them the 'hyperbolic', 'parabolic', and 'elliptical' cases.

The hyperbolic track would end with the core collapse of a massive star ($M_{ZAMS} \geq 7$–$8\ M_{\odot}$, and $M_{nucleus} \geq M_{Ch}$, M_{Ch} being Chandrasekhar's limit mass). These supernovae not necessarily would have hydrogen (remember the case of the binary star mentioned above).

The parabolic evolution corresponded to the case where the nuclear mass was only slightly superior to Chandrasekhar's mass, resulting in a type I explosion.

The elliptical case would occur in stars with mass $M \leq 4\ M_{\odot}$, whose nucleus have a mass inferior to that of Chandrasekhar's. During the red giant stage, the hydrogen envelope is lost via stellar wind and/or an episode of formation of a planetary nebula. The core remnant is transformed in a white dwarf, without supernova explosion.

Today, Shklovskii's physical classification seems very simplistic, and we can say at least that it cannot takes into account several important new clues (the influence of the metallicity on a supernova progenitor star evolution, just to mention one).

6. Is it Possible to Imagine an Alternative Physical Classification for Supernovae?

From the point of view of the MZ classification, Weiler and Sramek (1988) suggested that 'there is evidence that new results will further split these (types) into finer subclasses such as gradations between type II-L and type II-P and, possibly, other types such as Zwicky's types III, IV, and V'. From the discussions in Sections 3 and 4, we have seen that Zwicky's old types probably do not represent significant types of supernovae, and one must question the general way suggested by Weiler and Sramek (1988).

Perhaps the most important recent fact about supernovae's taxonomy be the new subdivision by Harkness and Wheeler (1990). They continue to use the old MZ scheme, in a different manner, in order to consider some recent new evidences. Also worth of mention is the work by Filippenko (1988c).

What parameters one must consider to build a totally physical classification for supernovae? We propose that, by adopting a simple working hypothesis, one can conceive a physical systematization for supernovae remnants. The most obvious principle is that the nature of the progenitor star is the major determinant of a supernova explosion, as well as of its explosion mechanism. It conditions its spectral and photometric behaviour, and the type of remnant formed after the explosion. From our discussions in the previous sections, this principle is equivalent to say that any physical classification for supernovae must include at least four parameters: the metallicity of the progenitor star, its mass on ZAMS, the maximum luminosity, and its membership to a binary system.

By 'nature of progenitor star' we want to designate generically the set of physical parameters of the star, such as its M_{ZAMS}, rate of late mass loss, its luminosity, density, and chemical composition. The nature of the progenitor star is a highly 'symptomatic' element, because it conditions strongly the supernova display, as well as its explosion mechanism. Even some very deep phenomena, such as the production of neutrinos in the stellar core may be influenced by the star configuration before the explosion. Good discussions of many issues bearing on supernovae progenitors may be found in the review by Wheeler (1991) and Branch *et al.* (1991) have also emphasized the importance of the supernovae-progenitors connection.

7. An Alternative Physical Classification for Supernovae

According to the general discussions contained in the previous sections, we can tentatively classify supernovae into at least two large and distinct families, each with similar basic explosions mechanisms:

A – Collapsing supernovae.

B – Cataclysmic supernovae.

A still speculative third family could perhaps be considered: namely, the 'hybrid' supernovae, or type C (see Section 4.3 for a brief discussion of this possible type).

The general mechanism of explosion in type A supernovae is the core collapse of the star. Type B events are caused by 'explosions' (see below), and the term 'cataclysmic' is used here only to emphasize the relationship of these supernovae with the large and heterogeneous family of the cataclysmic variables (which includes, e.g., classical novae, dwarf novae, etc.). In spite of the existence of fundamental physical discrepancies between these stars and supernovae, we remember that word 'cataclysmic' is more adequate to describe the nature of the explosive phenomena which occur mainly in type Ia supernovae. These supernovae involve a binary system, and mass capture by a compact object, that is, a general picture remembering the environment proposed to the cataclysmic variables, although the energy scale and the physical details of the explosions and their mechanisms are very different, in each case.

We now briefly comment about each class and their probable subtypes, always looking for correlations with the traditional MZ types, when this seems possible.

7.1. Collapsing supernovae

The explosion mechanism in this family is the core collapse and bouncing, occurring in old stars with $M_{ZAMS} \geq 8\ M_{\odot}$. It would be possible to divide them into two large subgroups:

A.1 – Canonical collapsing supernovae.

A.2 – Non-canonical collapsing supernovae.

Stars in subclass A.1 would presumably have a solar-like metallicity, and an upper limit on M_{ZAMS} equal to $30\text{–}40 \pm 20\ M_{\odot}$. At the moment of the explosion, the stellar configuration is a red supergiant, and this produces a classical type II event in the MZ classification, that is, one that can be included in type II-P or then in II-L, without peculiarities. These progenitor stars are not members of a binary system with mass transfer, and the result of the explosion would be a neutron star inside a plerionic expanding nebula.

If II-L supernovae are produced by stars originally more massive (i.e., those which experience a higher late mass loss), and II-P stars are descendent from progenitors which have more significant envelopes, then it is possible that the presence or absence of a plateau in the light curve be an indicator of the mass of the progenitor star. One could also deduce that II-P supernovae would be more common than II-L ones, because less massive stars are more abundant in nature. In fact, this is suggested by an analysis of the sample of Barbon *et al.* (1979). This picture is also consistent with the possibility that there could be a continuous sequence in the light curves morphologies, starting with a very evident plateau and ending in a linear light curve. It is also in agreement with the gradients in nitrogen abundances found by Chugai (1986).

If we accept the statistics by Maeder (1987), then it is possible that about 85% of all type II classical supernovae correspond to our physical type A.1.

It is highly tentative to conceive an additional splitting of A.1 subfamily of supernovae, representing a crescent hierarchy in mass of progenitor stars. Those stars with $8 \leq M_{ZAMS} \leq 10\ M_{\odot}$ experience the explosive ignition of oxygen simultaneously to the electron capture by ^{20}Ne and ^{24}Mg. These stars show evident plateaus in their light curves, and a possible example would be SN 1969L.

If the star has $M_{ZAMS} \sim 10-11\ M_{\odot}$, theoretical models suggest that the trigger of the supernova explosion is a combination of photodisintegration and electrons capture. These stars show an enrichment of helium in their ejecta, and a possible example could be SN 1054 (CM Tauri).

In the case where the $11 \leq M_{ZAMS} \leq 30-40 \pm 20\ M_{\odot}$, the probable explosion mechanism is only the electrons capture. The light curves of these supernovae show inconcpicuous or even no plateaus at all, and an extreme example could be SN 1979C (II-L). The radio observations by Weiler *et al.* (1991) also seem to suggest that the progenitor star of SN 1979C has lost more than 1 solar mass through the presupernova stellar wind, indicating that the star's mass was originally $M_{ZAMS} \geq 13\ M_{\odot}$.

In general terms, canonical collapsing supernovae should be very easy to identify because they correspond to the traditional II-P and II-L MZ types, showing complex spectra with hydrogen lines with P-Cygni profiles. They also present a gradient in the nitrogen abundance (Chugai, 1986) varying from $[N/O] \leq 1$ through $[N/O] \geq 2$, and always produce a neutrino pulse. These supernovae are also radio-emitters (mainly the II-Ls), presenting a flat spectrum ($\alpha = -0.6$), and a slow flux decay proportional to $t^{-0.7}$. This radioemission is provoked by the interaction of the supernova ejecta with the envelope derived from the mass loss during the red supergiant phase (RSG) before the explosion. In fact, the apparent absence of radioemission among II-P supernovae may be an additional evidence that they derive from less massive progenitor stars, which have experienced a lower mass loss during the RSG phase.

In the late phases of evolution, one could also expect to find infrared emission, due to dust grains condensation.

Non-canonical collapsing supernovae (A.2) are also produced by core collapses, but they do not derive from red supergiants. Instead, they descend from highly massive and evolved stars, or then from less massive stars deprived from hydrogen, and/or pertinent to poor-metallic progenitor populations.

For obvious reasons, one could expect that these non-canonical less massive collapsing supernovae be, so far, the commonest in their class, and we are effectively observing some examples of them: SN 1987A, and some of the Ib supernovae. The upper limit on mass to their progenitors in any case may be $M_{ZAMS} \sim 30-40\ M_{\odot}$, with a probable uncertainty of 50%, that is, the same to the canonical collapsing supernovae we have discussed above.

As the prototype of non-canonical submetallic collapsing supernovae (let us call this subfamily as A.2), we suggest SN 1987A, although other examples (poorly observed) could be mentioned. This class of objects would correspond to our proposed type II-B in the MZ scheme (see da Silva, 1990a, b).

It is interesting to mention, at this point, that, if a star with $M_{ZAMS} \sim 25\ M_{\odot}$ as was the case of Sk − 69° 202 placed in a submetallic galaxy such as the Large Magellanic Cloud already experiences the 'blue–red–blue' evolution before its non-canonical explosion, then, if there is canonical collapsing explosion in that galaxy too, one could expect all of them to be descending of less massive progenitors, probably producing only II-P light curves. If Maeder's statistics (Maeder, 1987) are correct, then only about 2% of all collapsing supernovae occurring in nature would be of this subclass, being furthermore more frequent in small galaxies, populated by stars deficient in metals.

It could also be mentioned, by passing, that it is also possible the core collapse of a yellow submetallic supergiant (see Maeder, 1987), although this possibility can be very small in nature ($\leq 1\%$ of all collapsing supernovae), because the yellow supergiant phase transition is very fast and short. These stars could form another (still speculative) subfamily to the non-canonical collapsing supernovae.

The non-canonical hydrogen deficient collapsing supernovae (thereafter A.22) typically derive from stars with $10 \geq M_{ZAMS} \geq 20\ M_{\odot}$ which have lost their hydrogen envelopes, e.g., experiencing mass transfer in a binary system. The loss of the envelope can be incomplete at the moment of the explosion, so there may be some hydrogen present in the spectra of these supernovae (this could be the case of SN 1987K, see Filippenko, 1988a). Supernovae A.22 can be producing a large fraction ($\gg 50\%$) of the types Ib and Ic events we are observing today.

The most probable remnants deriving from non-canonical hydrogen-deficient, or submetallic collapsing supernovae are neutron stars.

It is still possible to consider the existence of exploding Wolf–Rayet and Very Massive Stars (VMSs), although those could be very rare indeed. Supernovae from WR stars could represent about 10% of all collapsing explosions, and VMSs only $\leq 0.5\%$, if they exist at all! Both of them could be explosions without hydrogen lines but, in the case of VMSs, it is possible that the core collapse occurs while the star still have a hydrogen envelope.

Non-canonical WR-derived collapsing supernovae result from the core collapse started by pair instability, producing very subluminous ($M_V \sim -14$ to -16) explosions. A possible candidate to this class was the star progenitor of Cassiopeia A. Some Ib and Ic supernovae may also represent WR final explosions. An exploding Wolf–Rayet star would produce a supernova with proper characteristics. An exploding Wolf–Rayet star would produce a supernova with proper characteristics. They would be events with no hydrogen lines, showing a strong correlation with H II regions, probably more abundant in those galaxies which experienced recent active star formation episodes. One should also expect nitrogen, carbon, or oxygen enrichments in their ejecta. The maximum expansion velocity in such supernovae may be of the order of 8500 km s^{-1} (Fesen *et al.*, 1988). Few ^{56}Ni would be produced by these supernovae (around

0.5 $M_{\odot}$, or even less than this). A neutrino pulse would be produced, probably with a final steep cut-off and, as a remnant, one could expect a black hole or, more probably, no bound remnant at all (because of the explosive oxygen burning).

The initial mass interval for the progenitor stars of non-canonical VMS-derived collapsing supernovae, if they exist, is $100 \leq M_{ZAMS} \leq 300\ M_{\odot}$ or more. Although very rare, these objects would eject a substantial mass, which could compensate their scarceness, making them important contributors to the interstellar medium metallic enrichment. A VMS-derived collapsing supernova would be, in principle, very easy to recognize, because its luminosity ($\geq 10^{53}$ ergs s^{-1}). They also produce a neutrino pulse, but theoretical models seem to suggest this would be the case only when the progenitor star have few angular momentum. The majority of neutrinos produced by the core collapse of a star with $150 \leq M_{ZAMS} \leq 500\ M_{\odot}$ possess energies between 3 and 20 MeV (Joutras and Cline, 1988), with a proper energy spectrum. This type of supernovae would be confined only to the very large H II regions, those like the Tarantula nebula, in the Large Magellanic Cloud. It is not certain these supernovae can form black holes as bound remnants, because the oxygen burning during the core collapse could disintegrate totally the star's nucleus. One could mention at least SN 1987F as a highly tentative example of this type of supernova (Filippenko, 1988d), although the evidences are not totally conclusive. There is also a small chance that this type of supernova can occur in the active galactic nuclei (AGNs), if the theory of 'Warmers' is correct (Terlevich and Melnick, 1985).

7.2. Cataclysmic supernovae

These stars would generically correspond to the Ia MZ-type, deriving from explosions in white dwarfs pertaining to binary systems. Thus, they represent a class entirely different from the collapsing supernovae. Indeed, one could even use the word 'anti-collapsing' in conjunction with those objects.

The explosions are started by nuclear deflagration and (possibly too) detonations of carbon or helium, producing remnants which can be so varied as a white dwarf and nothing at all.

This family would admit at least two subdivisions:

B.1 – Deflagrating cataclysmic supernovae.

B.2 – Detonating cataclysmic supernovae.

Deflagrating supernovae may be explained by the standard model mentioned in Section 2, and a typical example is SN 1981B.

If detonating supernovae occur in the Universe, then it is possible that there is some observational selection effect at work. Some observed supernovae can have been examples of detonating explosions (e.g., SN 1984A according to Graham, 1988; and SN 1991T, see Ruiz-Lapuente *et al.*, 1992). An additional highly uncertain subdivision would be permitted by theoretical models: namely, the occurrence of one or two detonations in the explosion process. A monodetonating supernova would generate from 0.1–0.2 to 0.8 $M_{\odot}$ of ^{56}Ni, producing a subluminous event (Nomoto, 1982), giving no bound remnant and producing spectra dominated by C and O lines. In the bidetonating version, the explosion would produce 0.8–1.4 $M_\odot$ of ^{56}Ni, and only 10^{-1} to 10^{-4} $M_\odot$ of mean mass elements. These supernovae would be overluminous, showing spectra with very evident iron lines.

On the other hand, Khokhlov (1991) have calculated delayed detonating models for a carbon/oxygen white dwarf, and Müller *et al.* (1991) have pointed out that observations with COMPTEL instrument aboard Gamma Ray Observatory (GRO) must be able to discriminate between deflagrating and detonating supernovae, based on early gamma-ray fluxes. An identical conclusion has been attained by Burrows *et al.* (1991). It is still interesting to mention that a delayed detonating supernova could produce a sufficient quantity of mean mass elements in order to have an optical spectrum indistinguishable from a classical deflagrating explosion.

7.3. 'Hybrid' supernovae?

This would be a speculative third possible family of exploding stars, mentioned by Iben and Renzini (1983). They would be derived from stars with $M_{ZAMS} \leq 8\ M_\odot$ with a hydrogen envelope and a carbon degenerate core with mass superior to Chandrasekhar's. The explosion mechanism is the carbon deflagration in the core, and no bound remnant results. The word 'hybrid' is justified because these would be supernovae with hydrogen lines in their spectra, remembering the canonical collapsing supernovae (without a neutrino pulse!), but caused by an entirely different explosion mechanism (which is very similar to that of most of cataclysmic supernovae referred above).

If hybrid supernovae do occur in nature, they could explain the existence of supernovae in the mass interval between the upper limit to the formation of a planetary nebula, and the lower limit to the canonical collapsing supernovae. Figure 1 summarizes the physical systematization presented in the text.

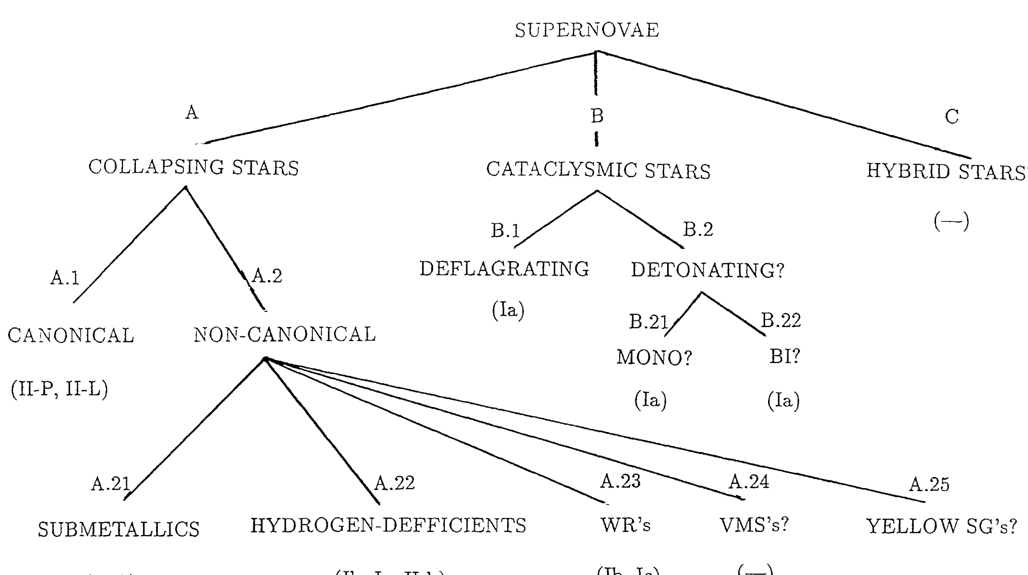

Fig. 1. A highly tentative scheme for a physical supernova classification, according to the discussions contained in the text.

8. Conclusion

With the systematization proposed in Section 7, it is possible, in principle, to remove some of the physical ambiguity contained in the traditional MZ classification. Our scheme does not take into account some old subdivisions, such as the still controversial types 'I fast' or 'I slow', although some correlations with these and others may be possible. Equally, we did not consider Pskovskii's photometric class β.

There are problems, of course. Such a physical classification is strongly dependent of observational criteria of diagnostics (OCDs), which are much more complex than the relatively simple OCDs used in the MZ classification. With the present status of the supernovae observations, this scheme could be applied only to very well observed and near stars, but it is possible that its radius of applicability can be extended in a near future, with the use of new technology telescopes and detectors, both ground-based and in space.

An important OCD to the general family of collapsing supernovae is the presence of a neutrino pulse. With the detectors available today, neutrinos from a galactic collapsing supernova could be detected, even that the explosion was not optically visible (Galeotti and Raiteri, 1988). Direct evidences show that such a detection is also possible for a supernova occurring in the Magellanic Clouds. The SUPERKAMIOKANDE detector (Koshiba, 1987) could extend the radius to a distance of 0.3 Mpc (still very near...). The detection of a neutrino pulse from NGC 224 or NGC 598 with the same intensity level that of SN 1987A would require detectors with 30 000 to 100 000 tons of liquid (Dopita, 1988).

Another point is that the classification considers basically only four physical parameters. However, it is certain that a more advanced scheme should take into account several additional elements (e.g., the final pre-explosion mass loss rates, and the quantity of the angular momentum of the progenitor star, to mention only two), although these further refinements seem premature today. An evolved physically based classification for supernovae would be multi-dimensional, and its use would show a very strong dependence with complex OCDs, so we must first to carry out more studies, both theoretical and observational, in order to understand the large and diversified phenomenology which characterize these dying stars, before consider the possibility of bulding such a scheme.

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