Low-Metallicity Star Formation:
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Supernovae and their Evolution in a Low Metallicity ISM

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Abstract. Observations of core collapse supernovae and their progenitors generally support expectations of increasing mass loss with increasing initial mass. Mass loss rates are expected to decline at lower metallicity, and there are prospects for directly testing this for the red supergiant progenitors of Type IIP supernovae. However, there are indications that mass loss rates for high mass early type stars may be overestimated and that there are mass loss mechanisms that do not decline at lower metallicity. In this case, there may be supernova emission from strong circumstellar interaction even at low metallicity. Although there is evidence for dust formation in freely expanding ejecta of supernovae, the quantities are relatively small. Another promising site of dust formation is the circumstellar interaction region, but this should occur in only a fraction of supernovae.

Keywords. Galaxies: abundances, stars: mass loss, supernovae: general, supernova remnants

1. Introduction

In recent years, the discovery of 100's of supernovae per year, as well as multiwavelength observations of these events, has clarified the landscape of supernova types. Mass loss during the stellar evolution is crucial for the type of supernova, and the mass loss properties near the time of the explosion can be investigated by multiwavelength observations. While the general supernova properties have been clarified for metallicities close to solar, there are puzzles regarding very massive stars and there remains considerable uncertainty in going to low metallicities.

In section 2, stellar evolution calculations of massive stars are considered. These calculations have become quite sophisticated, but still involve some assumptions that need to be examined. Observations bearing on these expectations are discussed in section 3. Dust formation by supernovae is discussed in section 4, and a concluding discussion in section 5.

2. Expectations from Massive Star Evolution

Evolutionary studies of single massive stars show that the properties of the supernova at the end of a star's life depend crucially on the mass loss leading up to the core collapse. At solar metallicity, estimates of mass loss as a function of stellar effective temperature and luminosity come from observations of stellar mass loss in the Galaxy. The result is that mass loss increases rapidly with mass, so stars with initial mass $\sim 9\ M_\odot$ end their lives with most of their H envelopes, while massive stars lose their H envelope by the time of the explosion. The transition to the loss of H envelope occurs at an initial mass $\sim 30\ M_\odot$ (Heger *et al.* 2003). Among the massive stars, at low metallicity there is also a transition to the point where the core becomes so massive that there is direct collapse to a black hole without an explosion, $\sim 40\ M_\odot$.

In going to low metallicity, the mass loss rates due to stellar winds are generally taken to have a dependence $\propto Z^n$ with $n \approx 0.5$ (e.g., Heger *et al.* 2003). For O stars and Wolf-Rayet stars there is some observational support for this dependence, but for red supergiants this is simply an estimate. Mass loss from red supergiants is likely to be a combination of hydrodynamic processes (e.g., pulsations or large convective cells) and radiation pressure on dust grains. The dependence on dust suggests a Z dependence, but the nature of the dependence is uncertain. The general implication of the metallicity dependence of mass loss rates is that at low metallicity, the fraction of stars that retain their H envelopes increases and one goes directly from supernovae with H envelopes to core collapses to black holes without normal supernovae.

One change among the supernovae in going to low metallicity is that the stars can end their lives as BSGs (blue supergiants, radii $< 100\ R_\odot$), as opposed to RSGs (red supergiants, radii $500 - 1500\ R_\odot$). In a study of $13 - 25\ M_\odot$ stellar models, Chieffi *et al.* (2003) found that all the stars at $Z = 0.02$ (solar) ended as RSGs, but that at $Z = 0.00$ all the stars ended as BSGs. At intermediate metallicities, the more massive stars tend to explode as BSGs and the less massive ones as RSGs. The progenitor radius is important for the peak luminosity of a supernova because the expansion from a small radius reduces the radiative energy in the supernova. Chieffi *et al.* (2003) estimate that the events with BSG progenitors are 1.5 magnitudes fainter than those with RSG progenitors.

Stars with initial mass $\geqslant 60\ M_\odot$ are subject to pulsational instability related to nuclear burning. Baraffe *et al.* (2001) find that at $Z = 0$, the instability is slow and relatively unimportant, but even a minute metallicity $\sim 10^{-6}$ is sufficent to give substantial mass loss by pulsations. Stars of somewhat higher mass, $140 - 260\ M_\odot$, are subject to become pair instability supernovae. In these events, the core becomes so hot that pairs form, causing the adiabatic index to drop below 4/3 and resulting in the collapse of the core region. The contraction leads to enhanced burning and explosion. At 140 $M_\odot$ there is weak Si burning, an explosion energy of 3×10^{51} ergs, and synthesis of a trace amount of ^{56}Ni, while at 260 $M_\odot$, the explosion energy is 100×10^{51} ergs, with the synthesis of up to 50 $M_\odot$ of ^{56}Ni (Scannapieco *et al.* 2005). These events clearly have the potential to produce very luminous supernovae. However, if there is mass loss during the stellar evolution, the core does not grow to the mass necessary for the pair instability to occur. With standard mass loss rates, pair instability supernovae are not expected for metallicities near solar because of the mass loss (Heger *et al.* 2003).

These results are modified in the case of close binary stars. Binary interaction can result in the loss of the H envelope in cases where single star mass loss would not be able to bring it about. In addition, the merger of stars can lead to a more massive H envelope than would occur in the single star case.

In the standard view, stars with initial masses $\geqslant 40\ M_\odot$ collapse to black holes. However, it is possible that a disk forms around the black hole and the energy generated by accretion is sufficient to blow up the star. This is a possible model for long duration gamma-ray bursts (GRBs) (Woosley 1993). A problem is that in the evolution of single stars, the core does not end up with enough angular momentum to form an accretion disk. This problem is alleviated by having relatively little mass loss during the evolution because the mass loss carries away stellar angular momentum. However, the supernovae observed to be associated with GRBs are of Type Ic, which do not have their H envelopes, implying mass loss. Yoon & Langer (2005) and Woosley & Heger (2006) suggested a possible solution to this problem, noting that a rapidly rotating main sequence star can completely burn because of rotational mixing, resulting in a Wolf-Rayet star even though there has been little mass loss. In order to avoid too much mass loss, the mass loss rates must be much less than the commonly used values at solar metallicity.

3. Implications of Core Collapse Supernova Observations

Observations of the basic core collapse supernova types near solar metallicity, IIP (plateau light curve), IIL (linear light curve) and Ibc (no H), are consistent with the general theoretical expectations. Modeling the light curves of SNe IIP had long shown consistency with the explosion of RSGs at the ends of their lives. In recent years, there has been direct observations of the progenitors of SNe IIP, showing that they are the expected RSGs (Li *et al.* 2007 and references therein). In addition, radio and X-ray observations have shown evidence for the mass loss rates expected for RSGs at the ends of their lives (Chevalier *et al.* 2006). The mass loss rates are expected to depend both on the mass of the progenitor star and its metallicity. The mass can be estimated from the direct progenitor detection or from modeling the supernova light curve, and the metallicity from observations of the surrounding ISM. Although the data are not yet of sufficient quality to do this, it may eventually be possible to directly measure the relation between mass loss rate and metallicity for the supernova progenitors.

As noted above, at very low metallicity these stars should explode as BSGs. Such events should stand out by their light curves, but have not been observed, only part of which can be explained by the fainter magnitudes that these supernovae have (Cappellaro *et al.* 1997). The implication is that we are not observing supernovae in very metal poor regions. The only supernova that clearly exploded as a BSG was SN 1987A and, in that case, it is plausible that the reason was a binary merger (Podsiadlowski *et al.* 2007). The asymmetric circumstellar medium around SN 1987A supports the merger scenario. Although the Large Magellanic Cloud is somewhat metal poor, it is not sufficiently metal poor to regularly result in supernovae exploding as BSGs.

The supernova Types IIL, IIb, and Ibc are consistent with the expectation that as one goes to higher initial mass, there is less of a H envelope left at the time of the explosion. Binary interaction can also give rise to a low mass H envelope; evidence for such an action is clearest for SN 1993J, where the binary companion has apparently been detected in the postsupernova light (Maund *et al.* 2004).

A supernova type that has been more perplexing is the IIn, which is characterized by relatively narrow Hα emission and a blue continuum (Schlegel 1990). The luminosities observed to late times for some of these objects are indicative of high rates of mass loss $\dot{M} \sim 10^{-3}(v_w/10 \text{ km s}^{-1})$ $\text{M}_\odot \text{ yr}^{-1}$ (e.g., Chugai & Chevalier 2006). In addition, P Cygni profiles observed in the Hα line indicate circumstellar velocities of 100’s km s^{-1}. Smith & Owocki (2006) make the point that the mass loss rates and velocities are higher than those in the winds of RSGs, and are roughly compatible with observations of LBVs (luminous blue variables), which are thought to be stars with initial masses $\geqslant 40-50\ M_\odot$ that do not go through a RSG phase. In the standard view of stellar evolution, these stars would go through an extended Wolf-Rayet phase after losing their H envelopes. The supernovae would then not interact directly with the dense mass loss. However, if the mass loss rate during the O star phase has been overestimated, it may be possible to have the supernova be nearly contemporaneous with the LBV phase. The cause of mass loss during the LBV phase is poorly understood; it may have to do with continuum opacity or with explosive events. Smith & Owocki (2006) note that these mechanisms do not have a metallicity dependence, so that the strong mass loss can occur even at low metallicity, in contrast to the standard view that going to low metallicity should lead to a lower circumstellar density at the time of the supernova. In this case, Type IIn supernovae could persist to low metallicity.

One development in the search for supernovae has been the implementation of ‘blind’ searches. Traditionally, supernova searches have targeted nearby luminous galaxies. In some of the new searches (e.g., the Texas Supernova Search (TSS) with the ROTSE-IIb telescope) a wide field of view is observed without targeting particular galaxies. Such searches have the potential to discover supernovae in small, typically metal poor, galaxies and luminous, distant, rare supernovae. These searches have found a number of Type IIn supernovae, although there are not sufficient statistics to comment on the rate of these events.

An interesting discovery from the TSS survey is the very luminous SN 2006gy (Smith *et al.* 2007; Ofek *et al.* 2007); the radiated energy in the first 200 days was $\sim 10^{51}$ ergs, comparable to the total mechanical energy of a normal supernova. One suggestion for the high luminosity is that the event was a pair instability supernova, with the creation of 22 $M_\odot$ of ^{56}Ni (Smith *et al.* 2007). The prediction of this model would be the presence of a late tail to the light curve, powered by radioactivity. Although the supernova has become very faint at optical wavelengths, it has become infrared bright (Smith *et al.* 2008b), which may require a radioactive power source. However, the metallicity of the host galaxy of SN 2006gy is roughly solar (Ofek *et al.* 2007), which is above the range expected for the occurrence of pair instability. This scenario requires an unexpected low rate of mass loss from the progenitor star. An alternative to radioactivity is power from shock interactions, but strong X-ray and radio emission, a signature of circumstellar interaction, has not been detected. However, absorption effects at high density could be the reason for the lack of emission (Ofek *et al.* 2007). Future multiwavelength observations should be able to discriminate between these possibilities.

Some of the best evidence for the expectation that GRBs have low metallicity progenitors has come from estimating the metallicity of the local environment of nearby GRBs and broad-lined Type Ic supernovae (Modjaz *et al.* 2008). The GRB related objects are systematically at lower metallicity, with the dividing line between them at [12+log(O/H)]= 8.5. However, if the solar O abundance is [12+log(O/H)]= 8.7, the metallicity of the most metal rich GRB event, GRB 980425/SN 1998bw, is only slightly below the solar value. Among more distant GRBs, there is some evidence indicating that GRB host galaxies have lower metallicity than other galaxies at a similar redshift (e.g., Fruchter *et al.* 2006).

There is not yet much observational information on supernovae in low metallicity galaxies. Based on broad Hα emission, Izotov *et al.* (2007) found possible evidence for Type IIP and IIn supernovae in metal poor blue compact dwarf galaxies. Interestingly, the possible Type IIn supernovae were only present in galaxies with [12+log(O/H)]$\leqslant$ 8.0, or 5 times lower than the solar value. However, the time dependence of these objects still needs to be demonstrated to show that they are indeed supernovae and not active galactic nuclei. Isotov (this meeting) found little time evolution in the Type IIn candidates over 5 years, implying that they are likely to be active galactic nuclei. The Type IIP candidates remain uncertain.

Prieto *et al.* (2008) have examined the relation between supernova type and host galaxy metallicity for > 100 supernovae found in the recent SDSS survey; the host metallicities span the range $\sim 0.1 - 2.7\ Z_\odot$. They find that the Type Ibc supernovae tend to occur in more metal rich galaxies than the Type II's, as expected from the general scenario of stellar evolution described in the previous section. However, the supernova that they find in the most metal poor galaxy ($Z \sim 0.05\ Z_\odot$) is a Type Ic, SN 2007bg. Interestingly, this supernova is a luminous radio source (A. Soderberg, private communication), which suggests that it has a dense circumstellar medium. Prieto *et al.* (2008) suggest a link to GRBs, but this supernova showed evidence for high velocity H and He absorption lines (Harutyunyan *et al.* 2007), which have not been seen in supernovae associated with GRBs. The supernova thus appears to be a normal broad-lined Type Ibc supernova, perhaps similar to SN 2003bg, that is well below the dividing line found by Modjaz *et al.* (2008).

4. Ejection of Dust by Supernovae

Dust formation in freely expanding supernova ejecta has long been predicted, but has been difficult to observe. SN 1987A provided a clear case of dust formation, as judged by a shift in the emission to infrared wavelengths and absorption of redshifted gas, but the amount of dust formed, $\sim 5 \times 10^{-4}\ M_\odot$ (Ercolano *et al.* 2007), was small. Considering the available mass of refractory elements, the efficiency of dust formation was $\sim 10^{-3}$. There have been numerous infrared observations of more recent supernovae, but the dust emission can generally be interpreted in terms of circumstellar dust. One case with dust formation in the ejecta is the Type IIP SN 1999em (Elmhamdi *et al.* 2003), but, once again, the amount of dust is estimated to be relatively small. In the case of the Type IIP SN 2003gd, Sugerman *et al.* (2006) found evidence for $0.02\ M_\odot$ of dust, which would imply a relatively high efficiency of 0.1 for dust formation. However, Meikle *et al.* (2007) find that Sugerman *et al.* (2006) overestimated the amount of dust and that only $4 \times 10^{-5}\ M_\odot$ of newly condensed dust is needed. They attribute some of the infrared emission to an echo. They note that the absorption of redshifted gas estimated from line profiles is comparable to that observed in SN 1987A, so that a comparable amount of dust may be indicated.

In recent years, another possible site of newly formed dust has drawn attention. When there is supernova interaction with a dense circumstellar medium, cooling shock waves may occur in the shocked region, allowing the temperature to drop to the point where dust condensation can occur. Because of the high pressure in the interaction region, the gas densities can exceed 10^{10} cm^{-3}, which is higher than the density in the freely expanding ejecta. Pozzo *et al.* (2004) found evidence for this mechanism in SN 1998S, but an especially good case for dust formation in this situation is provided by SN 2006jc, where both a rising infrared flux and absorption in circumstellar line emission was observed (Smith *et al.* 2008a). However, Nozawa *et al.* (2008) found that although $\sim 1.5\ M_\odot$ of dust might be formed according to their condensation calculations, the observational evidence indicated the formation of just $\sim 10^{-3}\ M_\odot$ of dust. This mechanism should be important in supernovae where circumstellar interaction is especially strong, i.e. the Type IIn supernovae. Fox *et al.* (2008) recently argued for the importance of this mechanism for the infrared emission from the Type IIn SN 2005ip and suggested that it may be more generally applicable to SNe IIn.

The dust mass estimates given here are for warm dust ($T \geqslant 300$ K). There are no reliable limits on the amount of cool dust. However, in the radiation field of a supernova, the dust is expected to be warm unless it is shielded by optical depth effects.

In addition to young supernovae, it is possible to detect dust in supernova remnants. The Crab Nebula is thought to come from a star with an initial mass of $8 - 10\ M_\odot$, based on its element abundances, so it is plausibly the result of a Type IIP supernova and provides a good case of comparison for the supernovae. *Spitzer* observations of the Crab show evidence for dust emission, and an estimated dust mass $\sim 10^{-3}\ M_\odot$ (Temim *et al.* 2006), which is comparable to the supernova results. One can draw the conclusion that Type IIP supernovae are generally inefficient at forming dust.

5. Discussion

Our understanding of the lower mass core collapse supernovae is in good shape. The stars explode as RSGs that have had relatively little mass loss during their evolution. The mass loss at the time of the supernova can be investigated by multiwavelength observations and there are prospects for determining the variation of mass loss rate with metallicity.

For more massive stars, mass loss effects are strong and there is more uncertainty in the evolution. There are several indications that generally assumed hot star mass loss rates are overestimated: (1) Some Type IIn supernovae show evidence for circumstellar densities and velocities that are typical of LBVs. Ordinarily, LBVs would be expected to go through a Wolf-Rayet phase before becoming supernovae, but reduced mass loss may allow an explosion close to the LBV phase. (2) There is possible evidence for a pair instability supernova at a metallicity close to solar. Such an event requires a very massive star with a small amount of mass loss. (3) A plausible requirement for a GRB is a small amount of mass loss from the progenitor, so there is little loss of angular momentum during the stellar evolution. Although these considerations point to low mass loss rates, there are also requirements for high rates. The occurrence of SNe Ibc requires mass loss to end with a stripped star, unless the Wolf-Rayet star is formed by rotational mixing during the main sequence with little mass loss. The case of SN 2007bg is of special interest because because it is in a very low metallicity host and has radio evidence for a dense circumstellar medium. These objects point to another mechanism for driving the mass loss in some cases: binary interaction is a good candidate.

Observations of supernovae show clear evidence for the formation of dust in the ejecta, which is relevant to the origin of dust in the early universe. Observations of Type IIP supernovae indicate the formation of $\sim 10^{-3}\ M_\odot$ of dust in the freely expanding ejecta. A similar amount of dust has been inferred in the Crab Nebula, which might have its origin in a Type IIP supernova. This amount is considerably less that the $\sim 0.1\ M_\odot$ of dust per supernova needed to produce the dust that may be present in the early universe (Todini & Ferrara 2001). A possible solution is that most of the metals in the universe are not produced by Type IIP supernovae, but by supernovae with more massive progenitor stars.

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