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ON RELATIVE SUPERNOVA RATES AND NUCLEOSYNTHESIS ROLES

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ABSTRACT

It is shown that the ^{56}Ni–^{56}Fe observed in SN 1987A argues that core collapse supernovae may be responsible for more than 50% of the iron in the galaxy. Furthermore, it is argued that the time-averaged rate of thermonuclear-driven Type I supernovae may be at least an order of magnitude lower than the average rate of core collapse supernovae. The present low rate of Type II supernovae (below their time-averaged rate of about one every 10 years) is a result either of the fact that the past rate was much higher or of the fact that many core collapse supernovae are dim like SN 1987A. However, even in this latter case they are less than a factor of 10 dimmer than normal Type II's due to the contribution of ^{56}Ni decay to the light curve.

Subject headings: nucleosynthesis — stars: supernovae

I. INTRODUCTION

Recent observational and theoretical developments with respect to supernovae have provided interesting and important constraints on the contributions of supernovae of Types I and II to galactic nucleosynthesis. In particular, theoretical modeling of the light curves of Type I supernovae has led to the conclusion that approximately 0.7 $M_\odot$ must be ejected in the form of ^{56}Fe(^{56}Ni) (Arnett 1988; Woosley 1988). More recently, observations of SN 1987A indicate an exponentially falling light curve with a lifetime compatible with ^{56}Co decay; the observed luminosity and distance dictate that approximately $0.07(d/50 \text{ kpc})^2$ $M_\odot$ (where d is the distance to SN 1987A) of matter was ejected in the form of nuclei of mass $A = 56$ in this Type II supernova event. We thus now have available, for the first time, a measure of the relative contributions of supernovae of Types I and II to the abundance of ^{56}Fe in galactic matter. We briefly explore some interesting possible constraints these mass estimates permit us to impose on galactic chemical evolution and on the rates of supernova activity over the histories of our Galaxy and other galaxies.

II. DEFINITIONS

To avoid many of the misconceptions that persist in supernova rate discussions, it is imperative that we define terms. In particular, we want to isolate the internal physics of an event from the traditional astronomical classification based on the character of the external optical outburst.

The optical outbursts have traditionally been split into two major categories: Type I (no hydrogen, $L \sim 10^9$ $L_\odot$, $V_{\rm rms} \sim 10^4$ km s^{-1}) and Type II (hydrogen, $L \sim 10^8$ $L_\odot$, $V_{\rm rms} \sim 5000$ km s^{-1}).

Physically, Type II's are associated with young massive stars ($M > 10$ $M_\odot$) undergoing core collapse. Standard Type I's are associated with the thermonuclear detonation or deflagration of a C/O white dwarf. Rather than becoming involved in the inelegant details of traditional classification schemes (Type IB's, etc.), we will classify supernovae in this *Letter* by the physics, namely (1) thermonuclear explosion models and (2) core collapse models. The surface "weather," composition, and exterior structure, which determine how a traditional astronomer classifies supernovae, will be ignored, except when discussing observational predictions.

Note that from the physics point of view, a core collapse model produces a dense remnant (either a neutron star or a black hole) and ejects large amounts of the heavy elements from oxygen to iron. However, the Fe ejecta comes from near the ~ 1.4 $M_\odot$ core where all massive stars have similar structures (presuming that the 1.4 $M_\odot$ value is dictated by the presence of significant electron degeneracy pressure), while the oxygen and other intermediate elements come from the mantle where the mass of each region varies with the mass of the star. Although there is some small variation ($\sim 15\%$) of Fe core mass and its surrounding shell within initial main-sequence mass, such variation is small compared to the mantle variations. Therefore, the O/Fe ratio will vary with the mass of the star. As mentioned above, from SN 1987A we know that approximately 0.07 $M_\odot$ of Fe gets ejected. This amount should hold approximately for all core collapse models. While the possibility exists of black hole formation in the collapse of some massive stars, we believe the effects on our nucleosynthesis arguments are negligible for stars in the mass range $10 \lesssim M \lesssim 50$ $M_\odot$. The mass of oxygen ejected varies from perhaps ~ 0.1 $M_\odot$ for the extreme low end of the mass range (stars of mass ~ 10 $M_\odot$) to ~ 10 $M_\odot$ for the most massive core collapse events (masses $\sim$40–50 $M_\odot$).

Core collapse is the prime nucleosynthetic event; thermonuclear explosions skip the bulk of the intermediate mass nuclei on their way to creating iron. It is now widely believed that this almost complete conversion of burned fuel to Fe is what powers traditional Type I light curves, with their long decay time. Such powering necessarily demands that $>60\%$ of the core is converted to iron. The calculation by Thielemann, Nomoto, and Yokoi (1986) specifically predicts that sufficient iron-peak nuclei are formed to explain the powering of the light curve, while the yields of intermediate mass nuclei are insufficient to contribute significantly to the abundances of these nuclei in the galaxy.

III. INTEGRAL RATE OF CORE COLLAPSES IN THE GALAXY

Since the bulk of the heavy elements are ejected in core collapse events, the "average" rate of nucleosynthesis in the Galaxy gives us a good estimate of the average rate of core collapse events.

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Taking the mass of the disk of our Galaxy as $\sim 10^{11} M_\odot$, its age as $\sim 10^{10}$ yr, and the mass fraction of oxygen in the disk as $\sim 8.5 \times 10^{-3}$, one estimates the total mass of oxygen in the disk as $\sim 8.5 \times 10^8 M_\odot$. (The 4.5×10^9 yr age difference between the Sun and Galaxy and the apparent constancy in metallicity are taken into account in a variety of ways in different Galactic evolution models. For our purposes here, we are interested in the minimal necessary production and will make only a first-order estimate). The oxygen yields of massive stars increase sharply with the mass of the star. Detailed yield estimates have been carried out in a continuous series of calculations by Arnett and Weaver and Woosley and their collaborators (see Thielemann and Arnett 1985; Woosley and Weaver 1982; Arnett 1988; Woosley 1988). Although some differences exist from year to year and between the two groups, the numbers we will use in our arguments are a reasonable representation of the results and their spread. A steeply falling initial mass function of the Salpeter type would argue that the typical core collapse supernova is one with a mass near the lower mass cutoff (see Arnett and Schramm 1973). Such an object ejects $\sim 0.5 M_\odot$ oxygen. The mass average yield (see eq. [1] of Hainebach, Norman, and Schramm 1976) using a Salpeter mass function is slightly higher due to the higher oxygen yields of the more massive stars. The actual value is sensitive to the high mass cutoff on the mass function and to mass-loss assumptions. (Higher mass loss results in all stars above some mass to lose mass faster than they evolve, thus producing a cutoff; see Dearborn *et al.* 1978.) For reasonable choices, the mass-averaged yield ranges from 0.7 to 1.5 $M_\odot$ of oxygen. (Note that yields averaged as in eq. [1] of Hainebach *et al.* do not have a one-to-one correspondence with the yields of any particular mass star, but if one were to ask for a representative model, a 20 $M_\odot$ would work better than a 10 or 30 $M_\odot$ one.) For the steeper Scalo mass function, the averaged yields are correspondingly lower and can almost approach the yield of the "typical" supernova selected by number. To within the uncertainties, it seems that to produce $\sim 10^9 M_\odot$ of oxygen would require about 10^9 supernovae. Since these occurred over the $\sim 10^{10}$ yr galactic lifetime, this implies an *average* core collapse supernova rate of about one every 10 years over the history of the Galaxy.

Although there is about a factor of 2 uncertainty in this average rate, it seems clear that the average is higher than the currently observed visible Type II supernova rate from external Sb and Sc galaxies, which is about one every 50 years (see Trimble 1988; Vandenberg, McClure, and Evans 1987), also to a factor of ~ 2 accuracy plus the additional uncertainty of the scaling with $(H_0/100 \text{ km s}^{-1} \text{ M pc}^{-1})^2$. Even if other probable collapse-caused supernovae such as Type IB's are included, the visible rate is quite insufficient. The reason for this difference may be either that the past rate was much higher or that the observed Type II rate does not include a large fraction of the actual core collapse events. This latter possibility would occur if many core collapse events were no more luminous than SN 1987A or if they were embedded in dense obscuring regions, such as was the case for Cas A. (The degree to which objects like SN 1987A would have been missed in previous searches is still a matter to be determined).

Alternative approaches to finding supernova rates, such as remnant statistics, pulsar statistics, or X-ray heating of the disk, are plagued by model dependencies on lifetimes, beaming factors, hot X-ray chimneys, etc., and may be less reliable than the nucleosynthesis arguments.

Galactic evolution models can accommodate a present rate either equal to or below the average rate as long as the average is maintained overall. For example, constant rate models can utilize infall, outflow, or variable initial mass functions to fit abundance versus age data (cf. Tinsley 1975), while high early rate models have the star formation rate decrease with time to fit the data. Standard one-zone galactic evolution, models in the absence of infall or X-ray outflow with a constant IMF, do predict such decreasing rates as the available gas is used up. However, it should be remembered that a comparison of nucleosynthetic rates averaged over nuclearchronometers of different lifetimes argues that rates have not changed by more than a factor of ~ 2 (Meyer and Schramm 1986).

For the future it is clear that supernova searches need to be refined so that low-luminosity events such as SN 1987A can be seen in external galaxies. Note that because of the ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe decay, SN 1987A eventually reached a peak luminosity that was within a magnitude of a "normal" Type II, so with appropriate search techniques even such faint ones might be able to be observed in more distant galaxies. Of course, observations will be more difficult in high-luminosity galaxies than in low-luminosity dwarfs, so care must be taken to avoid biases.

This minimal luminosity from SN 1987A shows us that even with a blue envelope structure, the resulting collapse event yields an appreciable luminosity (within 1.3 mag of a normal Type II in this case). Therefore, searches sensitive to a factor of 10 (2.5 mag) fainter in luminosity should be successful regardless of whether or not the progenitor is red or blue, unless the object is embedded in a dense cloud. This avoids the complication as to whether or not red or blue progenitors are more or less likely in galactic disks.

IV. Fe YIELDS

Notice that, with an average core collapse rate of one every 10 years and the assumption that all core collapses produce 0.07 $M_\odot$ of Fe as did SN 1987A, core collapse events alone can produce about $10^8 M_\odot$ of Fe. This is sufficient to explain half the Galactic Fe abundance (the current iron mass fraction being 10^{-3} of the Cameron [1982] abundances). Therefore, within the uncertainties, thermonuclear event iron production may even be unnecessary to the Galactic iron production. Most likely, it is only comparable to the yields from core collapse events. Since thermonuclear Type I's produce 0.7 $M_\odot$ of Fe, this argues that the average Galactic rate of such events must be no more than their present extragalactic observed rate of one every 70 years (factor of 2 accuracy, again neglecting the additional ${H_0}^2$ uncertainty) (see Vandenberg, McClure and Evans 1987) or they would overproduce Fe. In other words, the rate of thermonuclear events (Type I's) must either be constant or decrease as one looks into the past (high redshift), whereas the rate of core collapse events must either be much, much higher in the past than the present observed Type II rate or the present collapse rate itself is about a factor of 5 higher than the observed Type II rate. In either case, high-redshift studies should find at least an order of magnitude more collapse events than thermonuclear events.

Obviously an important check on these arguments is to verify that other core collapse events such as Cas A and "normal" Type II's also produce about 0.07 $M_\odot$ of iron.

V. CONCLUSIONS

1. The integrated Type I (thermonuclear event) rates by number is $\sim 10\%$ of the corresponding rate of Type II (collapse) events.

2. The observed Type I thermonuclear rate today is $\sim 10\%$ of the average collapse event rate. This implies that the Type I rate can at best have remained constant in time over the course of galactic history and might even have been lower in the past.

3. From SN 1987A light curve characteristics, we can now identify collapse events with the production of approximately 0.1 $M_\odot$ of ^{56}Ni. Independent of surface "weather conditions" (whether red or blue), the luminosity should reach values within 1.5 mag of the values characteristic of Type II supernovae at maximum optical light. (Typical Type II's have $M_v \sim -16.8$; SN 1987A peaked at $M_v \sim -15.5$.)

4. We emphasize the importance of a survey aimed at the establishment of the rate of SN 1987 A–like events in galaxies. It is this rate (generalized Type II rate) that is relevant for neutrino searches. We also emphasize the need for a survey of Type II light curves to determine whether yields of ^{56}Ni of the order of 0.07 $M_\odot$ is statistically accurate for "normal" Type II's.

5. We predict that the rate of Type I events in galaxies at increasing redshift should not increase but rather should remain constant or perhaps even decrease. This may be consistent with the view that Type I events, associated with binary evolution, may become important contributors only after the first few billion years of the galaxy history.

6. The origin of about half (or more) of the iron in the disk of the galaxy lies in collapse events (Type II supernovae), and this iron tracks massive star deaths.

7. Metal abundance anomalies in extreme Population II objects might be attributed to massive star collapse events alone, since the O/Fe ratio in the ejecta is expected to vary with initial stellar mass. The contribution from massive stars ≥ 30 $M_\odot$ are characterized by O/Fe ratios several times solar, while stars of mass $M \approx 20$ $M_\odot$ yield approximately solar O/Fe (SN 1987A).

8. The presence or absence of ^{56}Ni(^{56}Co) as indicated by the light curves, provides a potential probe of the correctness of our arguments.

9. The ratio of the required integrated rate of nucleosynthesis events to the present rate of collapse events also holds important implications for galactic evolution. Nucleochrometer arguments imply constancy to a factor of ~ 2 accuracy.

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