CONTRIBUTIONS OF SUPERNOVAE TO THE CHEMICAL AND DYNAMICAL EVOLUTION OF THE ISM

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ABSTRACT: Supernovae of Types Ia, Ib, and II contribute, on average, 10^{51} ergs of turbulent energy to the interstellar medium for each 2 $M_{\odot}$ of new heavy elements. This permits a dynamical extension of the homogeneous one-zone model (with constant IMF and instantaneous recycling) that is familiar from studies of galactic chemical evolution. Chemically possible scenarios predict current kinetic energy inputs ranging from 10^{39} to 10^{40} erg yr^{-1} per solar mass of interstellar gas. Dynamical studies might narrow this.

I. THE R.M.S. SUPERNOVAE

Widely-believed current theory (Woosley and Weaver 1986) attributes Type II supernovae to core collapse in massive stars and classical Type Ia's to deflagration of carbon and oxygen to iron (etc.) in accreting degenerate dwarfs or merging degenerate dwarf pairs. The slightly fainter Type IIb's (distinguished by minor spectral differences and probable association with youngish stars) have been variously blamed on variants of both of the preceeding mechanisms (Tornambè and Matteucci 1987; Iben et al. 1987; Branch and Nomoto 1987; Uomoto 1986; Begelman and Sarazin 1986; Gaskell et al. 1986; Filippenko and Sargent 1986).

For the core collapse case, heavy element production depends primarily on initial stellar mass, $M_z = -7.5 + 0.5\, M^{MS}$, in solar masses (Fig. 1, derived from calculations by Arnett, 1978). The average over a stellar population with Salpeter initial mass function (x = -2), minimum mass for core collapse = 8 $M_{\odot}$, and maximum effective main sequence mass = 50 $M_{\odot}$ (Schramm 1989; stars of still higher initial mass shed so rapidly that their nucleosynthesis mimics that of lower mass stars) is 2.4 $M_{\odot}$ per event. An average kinetic energy of 10^{51} ergs in the ejected envelope is derived both from model light curves and from observed line widths, attributed to 5-10 $M_{\odot}$ moving at 3000-4000 km s^{-1}. Apparently the shock doesn't much care what is outside the bouncing core.

The average values apply also to several otherwise deviant SNIIs. The explosion that gave rise to Cas A either was very faint or went undetected (Ashworth 1980), but studies of the remnant show sizable excesses of heavy elements and an energetic shock moving out into the ISM. Since the remnant also contains hydrogen, we assume that the spectrum, if recorded, would have shown the defining lines of a Type II and that the energy source was core collapse, possibly to a black hole, since no X-rays attributable to a young, hot neutron star have been seen. Similarly for 1987A, models

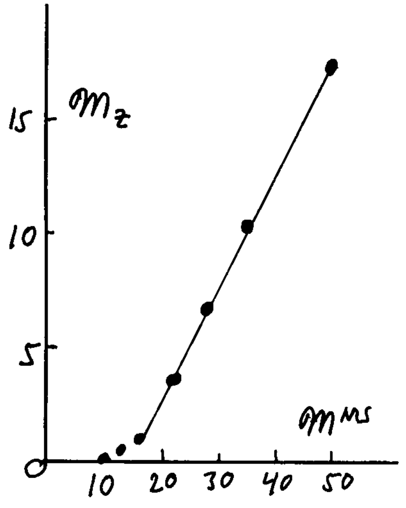

Figure 1: Mass of new heavy elements ejected by Type II, core collapse, supernovae, as a function of main sequence mass. Units are solar masses; models are those of Arnett (1978).

directed explicitly toward its progenitor indicate the synthesis of about 2.5 M_o of heavy elements (Hashimoto et al. 1989; Woosley et al. 1989) and an ejected envelope mass of 5-10 M_o. Since the time development of the line profiles showed the base of the hydrogen-rich envelope to lie at about 4000 km s^{-1}, the total kinetic energy (confirmed by models of the light curve) is the canonical 10^{51} ergs, despite the moderate faintness of the event.

Calculations directed toward SN 1987A have also made clear that moderate changes in initial composition and in nuclear reactions rates (especially the critical and uncertain $C^{12}(\alpha, \gamma)O^{16}$ rate) do not much affect the total amount of metal production, though they do modify the relative amounts of the major nucleosynthetic products (C,O, Ne,Mg,Si,S,Fe).

The supernova of 1954 is a curious exception to the pattern. The observed expansion energy of the remnant is at very most 10^{50} erg (1-2 M_o of line-emitting gas moving at less than 2000 km s^{-1}). And its contribution of new heavy elements is also negligible! (Davidson et al. 1982).

For the carbon detonation case, roughly a Chandrasekhar mass of heavy elements is necessarily kicked out into the world. Some of this will be newly-synthesized iron, some unburned CO, and some elements in between (the ratios impacting directly on the value of H_o found from SN Ia's and so not to be mentioned in polite company). Models of the light curves and confirming evidence from young supernova remnants tell us that the ejected kinetic energy is again about 10^{51} erg. If the current ratio of core collapse to deflagration supernovae is about two to one (van den Bergh et al. 1987), then the average over the supernova ensemble is 10^{51} ergs for each 2 M_o of new heavy elements.

II. THE HOMOGENEOUS, ONE-ZONE MODEL REVISITED

The first detailed models of galactic chemical evolution were numerical ones derived by Tinsley (1968). Shortly thereafter, Searle (1973) showed that some of the results could be arrived at analytically in the case where a galaxy constitutes a homogeneous, closed system, the birthrate of stars is a separable function of time and mass, and stellar nucleosynthesis occurs on a time scale short compared to anything else in the problem. This is called the homogeneous, one-zone model, with constant initial mass function and instantaneous recycling. Let u be the fraction of material in the form of gas, Z be the fractional metal abundance in the gas, and y be the yield (the fraction of material going into stars that comes out as heavy elements). Then chemical evolution is described as:

$$\frac{d(uZ)}{dt} = Z\frac{du}{dt} - y\frac{du}{dt}(1-Z) \qquad (1)$$

where the first term on the right represents loss of metals going into stars and the second term represents the gain from supernovae (notice that du/dt is intrinsically negative). After rearranging terms and assuming $Z \ll 1$, eqn. (1) has the solution:

$$Z = y \ln (1/u) \qquad (2)$$

which turns out to represent average galaxies, from irregulars to ellipticals, rather well. A little more manipulation leads to the predicted numbers of stars of various metal abundances as (where Z_o and u_o are the present values):

$$\frac{N(Z)}{N(Z_o)} = \frac{1 - u_o^{(Z/Z_o)}}{1 - u_o} \qquad (3)$$

Eqn. (3) presents the theoretical side of the classic G dwarf problem (meaning that we see far fewer old, metal-poor stars in the solar neighborhood than the model predicts). Other populations, including globular clusters and old giants in Baade's window are, on the other hand, well fit by the prediction (Pagel 1987).

If, instead of simplifying eqn. (1), we multiply it by the mass of the galaxy,

$$\frac{d(M_g Z)}{dt} = Z\frac{dM_g}{dt} - y\frac{dM_g}{dt} = Z\frac{dM_g}{dt} + k\frac{dE}{dt} \qquad (4)$$

is the result. The second term on the right can then be replaced by +k dE/dt, where dE/dt is the rate of input of kinetic energy into the gas and k is the 2 M_o per 10^{51} ergs produced by our rms supernova. Here and now, with a galactic gas mass of 7.35 X 10^9 M_o (8% of a disc with R = 8.5 kpc and V_c = 220 km/s) and $\Delta Z/\Delta t$ = 0.016/8X10^9 yr, we predict an input of 7 X 10^{48} erg yr^{-1} or 2.5 X 10^{47} erg per solar mass of gas per galactic rotation period. These numbers are not obviously in conflict with anything in particular. Closer examination of chemical enrichment history and its implications, however, reveals a wide margin of uncertainty, which dynamical considerations may be able to constrain.

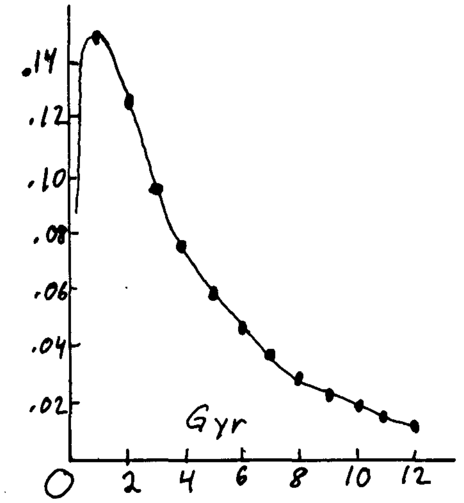

Figure 2: Rate of Type II SNe, in events per year, vs. age of the galactic disc in Gyr, from a model by Matteuci and Tornambè (1988)

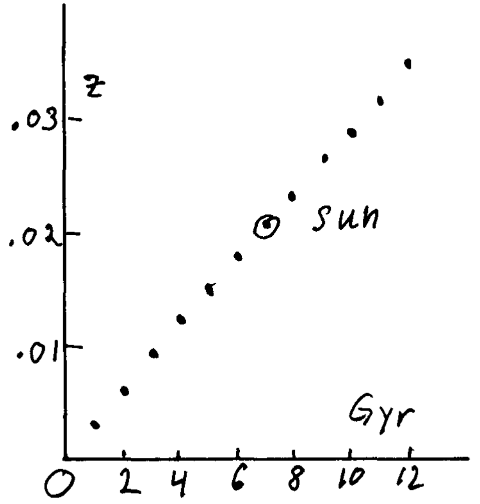

Figure 3: Change of gas metal abundance, Z, vs. age of the galactic disc in Gyr implied by the SN rates of Fig. 2. The exponential decline (t_e = 4.3 Gyr) is balanced by exponentially declining gas mass to yield a linear Z(t).

III. PAST AND PRESENT SN RATES AND THEIR IMPLICATIONS

A typical, successful, model of Milky Way chemical evolution (Matteucci and Tornambè 1988), incorporates SNII rates vs. time as shown in Fig. 2. Heavy element abundance in the residual gas is then as shown in Fig. 3. The value for the sun is tolerable, but the present Z_{gas} = 0.035 is clearly too high (compare Z = 0.018 for Orion, Peimbert et al. 1988, and [Fe/H] = -0.08 to +0.125 for six young clusters, Boesgaard 1989), though the present SNII rate is in good accord with that expected observationally (van den Bergh et al. 1987). In addition, our mental picture of galactic chemical evolution is really more like Fig. 4 or 5 than Fig. 3 (another way of saying that the G dwarf problem is peculiar to the solar neighborhood).

Consider the three components separately and quantitatively. For the halo, initial metallicity Z_i = 0 and final metallicity Z_f = 0.005, achieved over a time interval of at most 3 Gyr. Thus dZ/dt $\gtrsim$ 0.002/Gyr. For the disc component, maximum metallicity rises to Z = 0.01 in 3-4 Gyr, for a dZ/dt of about 0.002/Gyr. Finally, in the thin disc, Z rises by perhaps another 0.016 in about 8 Gyr, yielding dZ/dt = 0.002/Gyr yet again.

This would seem to correspond to a kinetic energy input of 10^{39} erg yr^{-1} per $M_\odot$ of gas over all of galactic history and a supernova rate of only 1/136 yr at the present time. But what are the real uncertainties?

Recent observational work (Capellaro and Turatti 1988, van den Bergh et al. 1987, Tammann 1982, Richter and Rosa 1989; see Trimble 1989 for further references) comes rather close to recovering Zwicky's (1938) supernova rate of (in modern units and

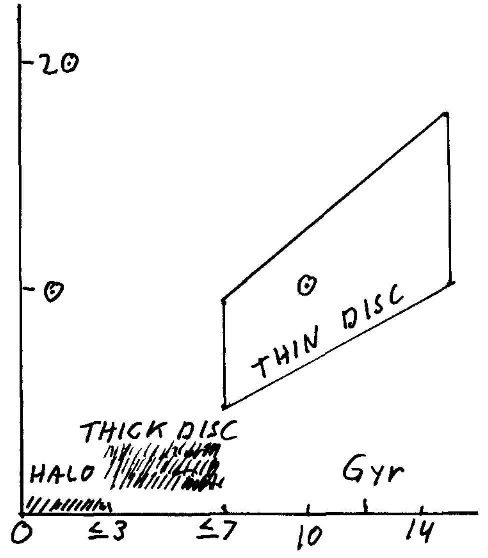

Figure 4: Scenario for galactic chemical evolution with three discrete stellar populations. Recent work on stars with large proper motions (Carney 1988) suggests such discreteness at least in the solar neighborhood.

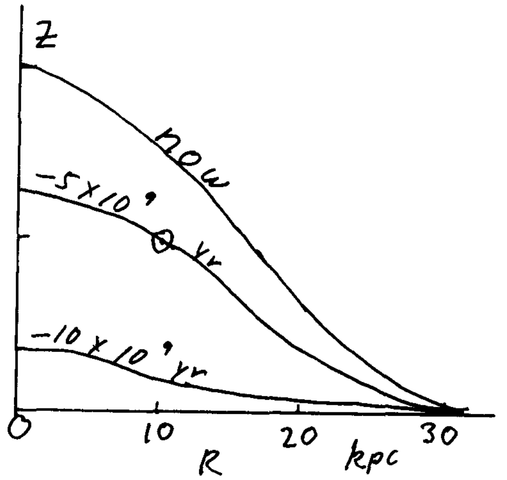

Figure 5: Scenario for galactic chemical evolution with continuous distributions in both space and time. Norris and Green (1989) find that this may be a more suitable picture than one with separable components.

distance scales) 1.7 h^2 SNe per century per 10^{10} $L_\odot^B$, or about 3.4 h^2 per century in the Milky Way, implying a kinetic energy input rate of 5 X 10^{39} erg yr^{-1} per $M_\odot$ of gas. Finally, Schramm (1989) has advocated one nucleosynthetic, core-collapse supernova every 10 years, which would feed 10^{40} erg yr^{-1} per $M_\odot$ of interstellar gas into the system. Thus I would like to ask the question: Can dynamical studies help to narrow down this order-of-magnitude uncertainty?

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Discussion:

MÜNCH (Comment): We have heard during this Meeting about the crucial role played by SN in determining the structure and physical state of the ISM, but little about their influence in the chemical composition of the local ISM. In this respect I should mention that last Summer Gerry Wasserbug exposed to me existing problems in our understanding of the high abundance of radionuclides Al^{26} in meteorites. Wasserburg believes that Astronomers are not fully aware of the implications of the isotopic anomalies, and for this reason promised me he would attend our Meeting. Since he could not make it, I can only repeat his plea to us for paying attention to the message contained in the early solar system material.