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Communication présentée à : 2. IAP Meeting on nuclear astrophysics
Paris (France)
7-11 Jul 1986

SUPERNOVA EXPLOSION IN A VERY MASSIVE STAR

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ABSTRACT

We describe the final evolution of a 100 solar mass star following an evolutionary scenario during which the star evolves from a Wolf- Rayet stage through the electron- positron pair creation supernova. We find that the star is completely disrupted by explosive oxygen burning, and this type of explosion as a possible scenario for the Cassiopeia A remnant. This scenario seems to be also applicable to the supernova 1985f according to the recent observations of this object.

KEYWORDS

Stellar evolution; Wolf-Rayet stars; pair creation instability; supernova explosion; nucleosynthesis; supernova remnants; Cas A

I. INTRODUCTION

Many observations performed in recent years (Massey and Hutchings, 1983; Humphreys, 1984) have shown the existence of very luminous stars like η Car, S Dor, and R136a in the galaxies of the local group. Such stars are interpreted (Maeder, 1984; Doom and co-workers, 1986) as the most massive stars with stellar masses well above 100 solar masses ($M_\odot$).

A possible evolutionary scenario for very massive stars (VMS) with $M \geq 80\ M_\odot$ is that they suffer extensive mass loss during the hydrogen and helium burning phases losing thereby the hydrogen-rich envelope to become a massive Wolf-Rayet (WR) star during helium burning. The WR star represents the final stage of a VMS evolution possibly being terminated by a pair creation supernova explosion (PCSN), which is different from type II (see Hillebrandt; Kahana, this volume) or type I supernovae (see Nomoto; Iben, this volume).

Many previous computations of the PCSN (see Wheeler, 1980, for a review) have been done only for oxygen stellar cores, and few others (Arnett, 1973; Woosley and Weaver, 1982; Ober and co-workers, 1983) have tried to relate the core mass to the initial mass of the star.

In a recent work (Langer and EL Eid, 1986), we investigated the evolutionary scenario for VMS mentioned above in the rather representative case of a 100 $M_\odot$ pop I star, and followed its quasi-

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[1] Seminar presented at the International School of Nuclear Physics (Erice, Sicily, April 1985)

static evolution up to the WR stage in order to study the influence of mass loss by stellar wind and convective mixing on the internal structure, the WR mass, and the nucleosynthesis products. The main characteristics of the models we have obtained are briefly summarized below, and they serve as initial models for the hydrodynamical calculations which are briefly described in this contribution. The main purpose of our calculations is to find out whether exploding massive WR stars could be possible progenitors of some of the oxygen-rich supernovae like Cas A.

Exploding massive WR stars have been envisaged by Cahen and co-workers (1986) to explain the light curve of some oxygen-rich supernovae, and recent observations (Filippenko and Sargent, 1986; Begelman and Zarasin, 1986) of the supernova 1985f suggest a massive WR star as its progenitor.

II. THE INITIAL MODELS

In Table 1 several parameters of the initial models are given. M_f designates the mass of the stellar core at helium exhaustion, M_{core} is the mass of the convective core before it shrunk to zero, and X denotes abundance mass fractions. Note that the numbers in brackets are powers of ten.

TABLE 1. Parameters of the Initial Models for the Hydrodynamical Calculations

Model	$M_f/M_\odot$	$M_{core}/M_\odot$	T_c (K)	ρ_c (g cm^{-3})	X_C	X_O	X_{Ne}	X_{Mg}
A	61.0	60.15	4.07(8)	1.35(3)	0.0386	0.853	0.0586	0.0502
B	45.2	42.80	3.98(8)	1.48(3)	0.0225	0.856	0.0652	0.0558

Model A has been obtained by assuming the largest amount of 'convective overshooting' predicted by currently used models for turbulent convection (Roxbourgh, 1978; Doom, 1985; Prantzos and co-workers, 1986). Overshooting means here mixing beyond the boundary of the convective core determined by the Schwarzschild criterion for convection. For comparison, the Schwarzschild criterion has been used to determine the size of the convective core in model B. As seen in Table 1, the central conditions (T_c and ρ_c) and the compositions are rather similar for both models with oxygen being the main constituent. However, due to the net effect of overshooting and mass loss, model A has the larger mass and resembles a WO star, while model B represents a WN star. The difference between these subtypes of WR stars is illustrated in Fig. 1 in terms of the surface abundances. A WO star exhibits enhancement of the He-burning products C and O, and diminished He and N, and a WN star shows enhancement of the CNO-burning products He and N at the expense of C and O.

III. THE HYDRODYNAMICAL CALCULATIONS

1. *Numerical method and input physics.* To follow the further evolution of the models presented above we have used an implicit hydrodynamical code which integrates the differential equations of conservation of momentum, energy, mass, the equation of radiative energy transport in the diffusion approximation, and the equation defining the velocity. We assume spherical symmetry, and replace the differential equations by difference equations, which are then solved iteratively with appropriate boundary conditions in a lagrangian grid for the variables, radius, velocity, temperature, density, and luminosity (r, u, T, ρ, L_r).

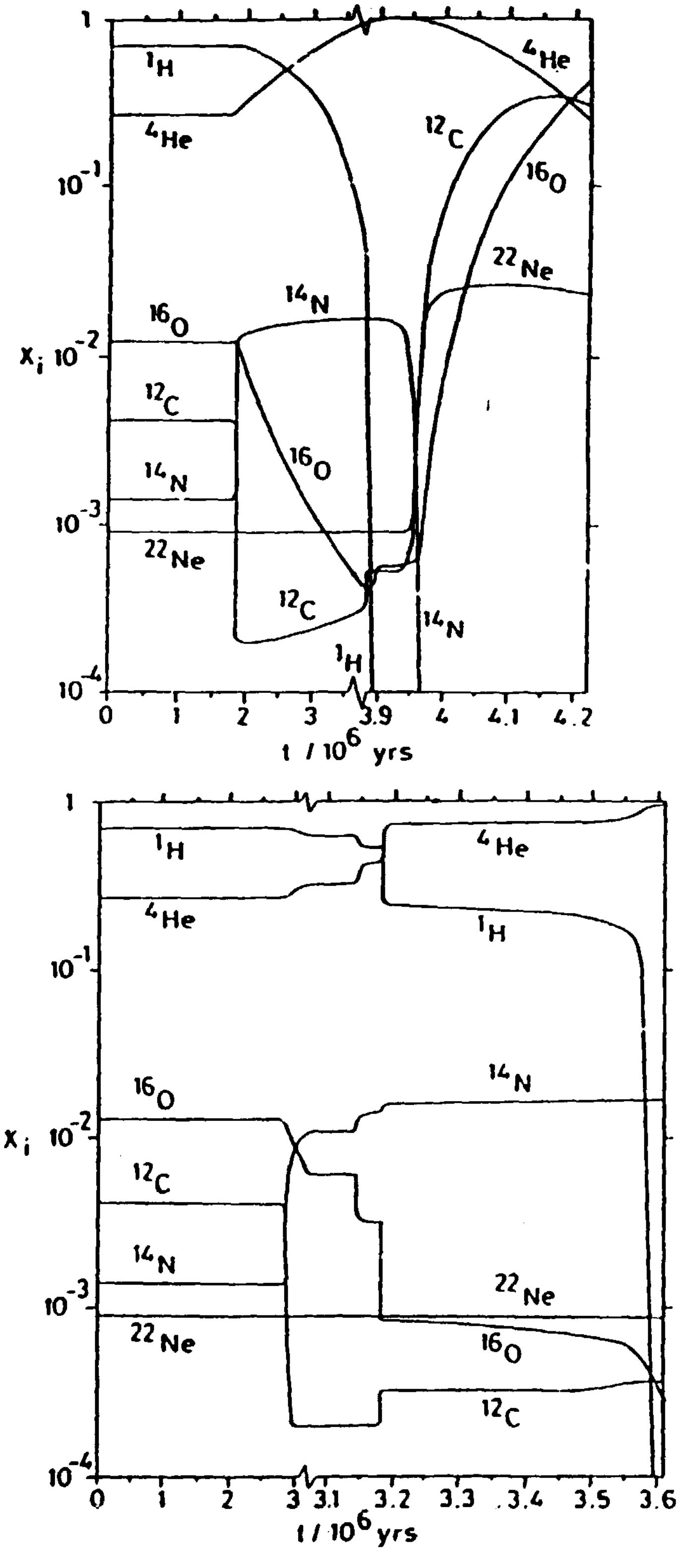

Fig 1. The change with time of the surface mass fraction of selected nuclear species during the hydrogen and helium burning phases of a 100 $M_\odot$ pop I star. Upper Fig. is for Model A, and lower Fig. for model B (see text).

The equation of state (pressure as a function of T, ρ, and compositions) is calculated including the effect of electron- positron ($e^{\pm}$) - pair formation. We consider a mixture of ions, black body radiation, and $e^{\pm}$- pairs in thermodynamic equilibrium, in which the ions are treated as a Boltzmann-gas to get their contribution. The contribution of the $e^{\pm}$- pairs is obtained by assuming that they are created by the radiation field via the equilibrium process $2\gamma \rightleftharpoons e^{-} + e^{+}$. Their chemical potentials are then related to each other by $\mu_{+} = -\mu_{-} - 2m_e c^2$. For given T and ρ we insert these chemical potentials into the relativistic Fermi-integrals and calculate the concentrations of the e^{-} and e^{+} under the constraint of charge neutrality (see Cox and Giuli, 1968 for more details). The result of such calculations is that the effect of pair formation is only important in a restricted region of the T - ρ plane with a maximum $\rho \sim 6.0\ 10^5$ g·cm^{-3} and T$\sim$ 2.7 10^9 K. These values are due to the fact that at higher densities the positron concentration is small since the electron gas becomes degenerate, and at higher temperatures the effect of pair creation is not important since the particles are relativistic. When a VMS evolves into the domain of pair creation, it becomes dynamically unstable, since this process is accompanied by the absorption of energy which causes the adiabatic index Γ to drop below 4/3 in large parts of the star (see next Sect.).

Neutrino energy losses have been included in our computations via the processes described by Beaudet and co-workers (1967), and the corrections factors for neutral currents are those of Ramadurai (1976). The opacity due to Thomson scattering has been adopted in the present calculations.

A simplified network of nuclear reactions has been coupled to the dynamical calculations to account for the energy generation and nucleosynthesis. This network contains 13 nuclei linked by the triple-alpha reaction, the (α,γ) reactions up to ^{56}Ni and their inverse reactions, and the α-channels of the C-C, C-O, and O-O reactions. Updated nuclear reaction rates (Caughlan and co-workers, 1985) have been utilized.

2. *Results.* In the following we only summarize the main results of our calculations; more details will be given elsewhere (cf. EL Eid and Langer, 1986). In both models A and B the evolution towards the carbon burning is mediated by a Kelvin- Helmholtz contraction phase which lasts about 10^3 yrs, and proceeds exceedingly fast due to enhanced neutrino energy losses.

In model A (see Fig. 2) C- burning and most of the Ne- burning occur with a global nuclear energy generation rate L_{nuc} less than the energy loss rate due to neutinos L_{ν}, which inhibits the formation of a convective core during these burning phases. The star encounters the $e^{\pm}$- pair instability already during Ne- burning within about 40% of its total mass (61 $M_{\odot}$) and starts collapsing to higher T and ρ values such that the central region of the star leaves the instability domain. At the same time explosive O-burning is initiated in the center which propagates outward reversing the collapse smoothly without shock formation, since the collapse velocities remain below the velocity of sound which is typically about 10^9 cm/s in our case.

In model A oxygen was ignited at the central values T_c=2.55 10^9 K and ρ_c=1.1 10^6 g·cm^{-3}. The collapse phase proceeded up to T_c=3.8 10^9 K and ρ_c=2.7 10^6 g· cm^{-3}, and about 10 $M_{\odot}$ of oxygen were consumed before the reversal of collapse into an explosion with a kinetic energy E_K=1.05 10^{52} ergs and a surface velocity of 6880 km/s. The explosion phase has been followed until all mass shell have achieved escape velocities so that no remnant is left in this case.

The model B (see Fig. 3) with the smaller core mass of 45 $M_{\odot}$ exhibited several different features compared with the previous one. Due to the rearrangements of the α- particles at the onset of Ne-burning L_{nuc} exceeded L_{ν} which induced a pulse throughout the star (see Fig. 3) with a duration of $\sim$ 2 10^4 s. This pulsational behavior did not lead to mass ejection, but it may explain why the pair creation instability occurred at oxygen ignition, i.e. later than in model A. Explosive O-burning was confined to the very central part of the stellar core owing to its smaller mass, and smaller peak values T_c=3.0 10^9 K and ρ_c=1.74 10^6 g· cm^{-3} were achieved. The collapse phase was reversed

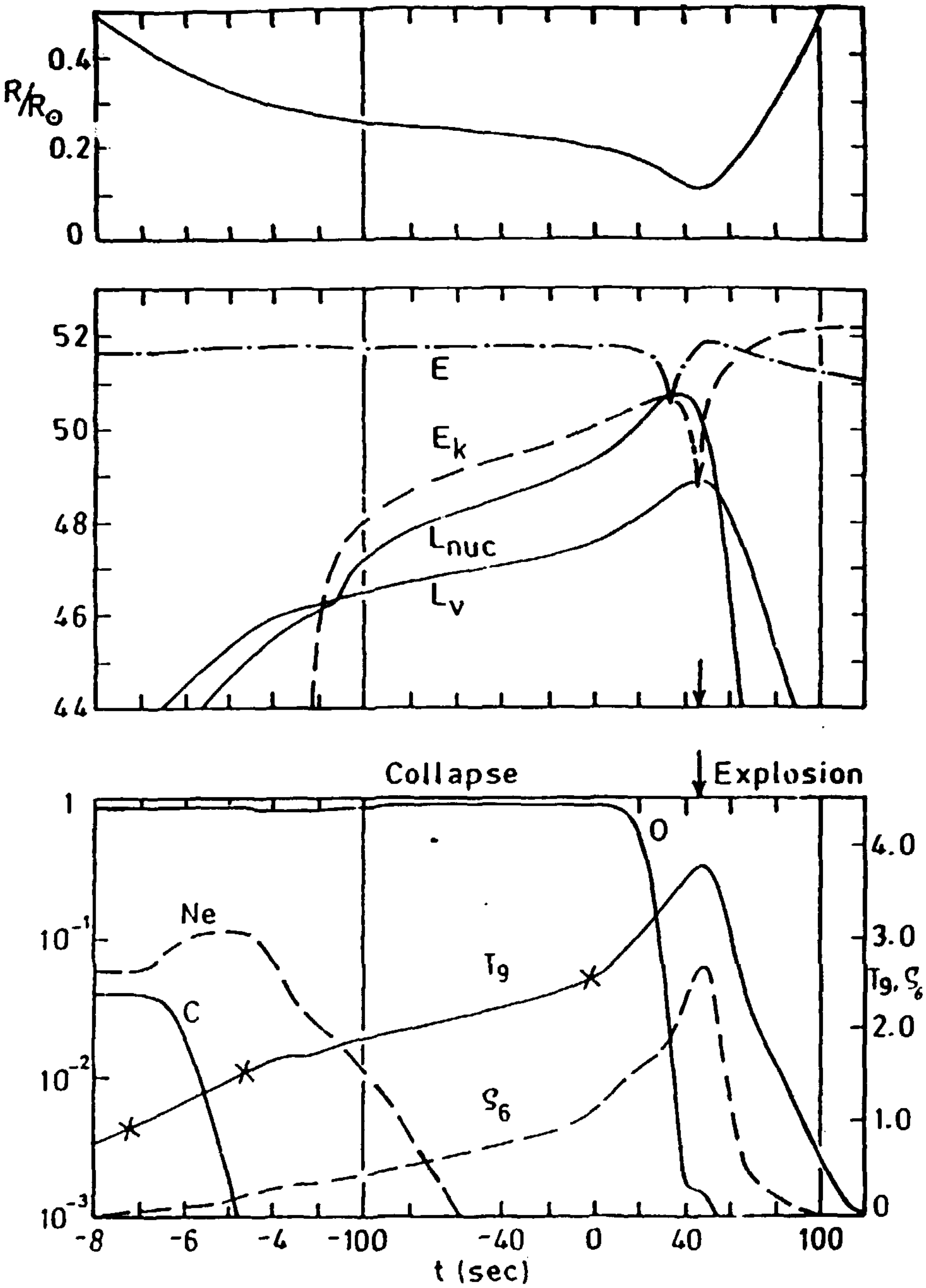

Fig. 2 The final evolution of model A. The time t=0 is chosen arbitrary at the onset of explosive oxygen burning. The time scale is linear in the interval (-100, +100) and logarithmic otherwise. The upper Fig. shows the radius of the star as function of time. The middle Fig. displays the logarithmic values of $E=|E_{pot}+E_{th}|$, (E_{pot} and E_{th} are the potential and thermal energy respectively), the kinetic energy E_k, the rate of nuclear energy release L_{nuc}, and the rate of neutrino losses L_ν, all are integrated quantities in cgs units. The lower Fig. shows the time evolution of the mass fractions X at the center for C, Ne, and O (left scale) together with the central temperature (10^9 K) and density (10^6 g cm^{-3}). Collapse and explosion phases are indicated.

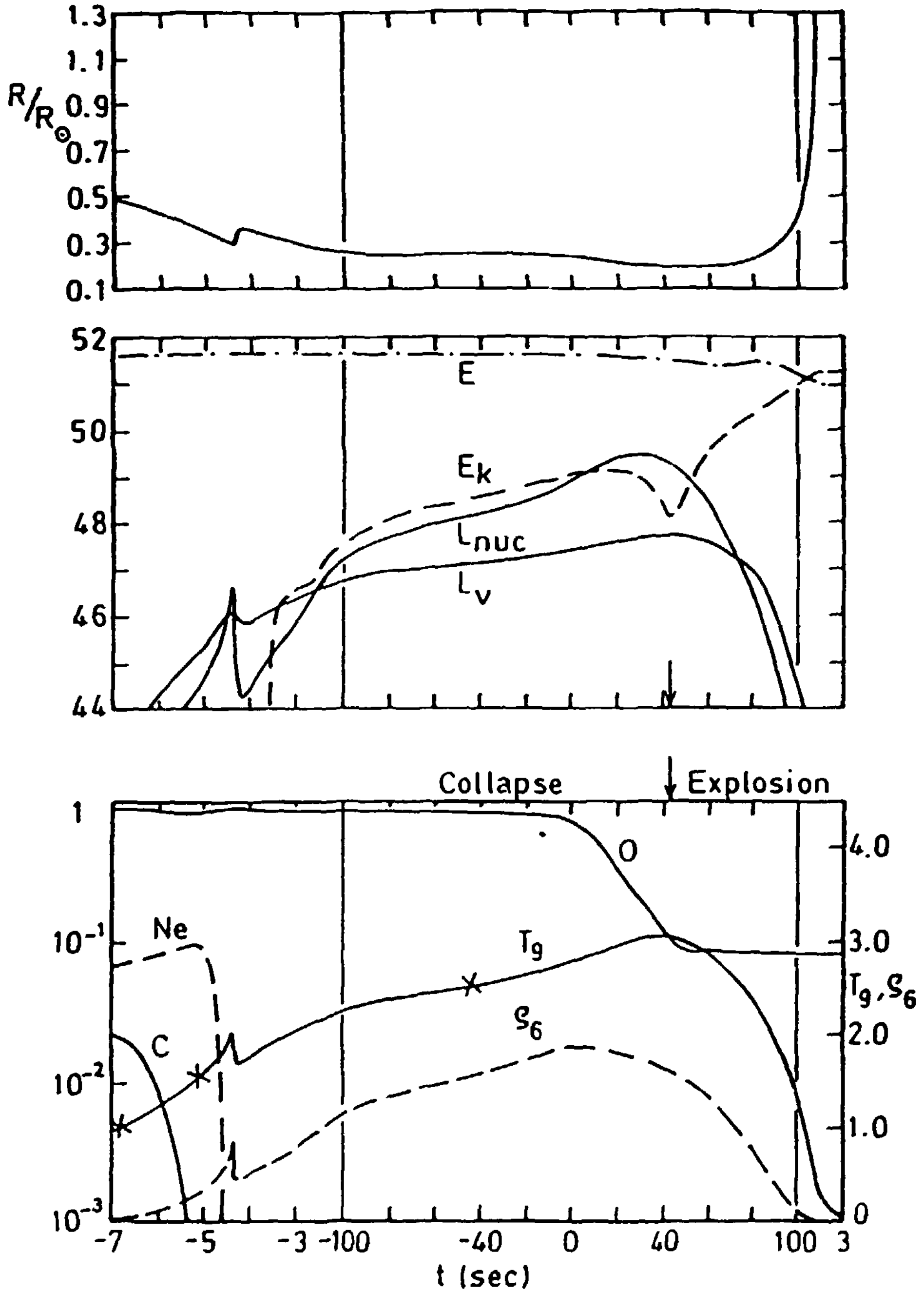

Fig. 3 Same as Fig. 2 for model B. Visible in this Fig. is the pulsational behavior of the star during Ne burning explained in the text.

into explosion with E_K=1.78 10^{51} ergs and a surface velocity of 4800 km/s. The explosion phase was followed until T_c=8.6 10^7 K, and ρ_c= 52 g·cm^{-3}, and the calculations were stopped after 15 $M_\odot$ of the star exceeded escape velocity. Probably this model also ends up with total disruption, and it seems to represent an upper limit for the so called 'pulsational pair instability' found in the computations of Woosley and Weaver (1986), who also evolved a 100 $M_\odot$ star obtaining a 45 $M_\odot$ WR star at helium exhaustion. This star encountered the pair creation instability and collapsed to similar peak values of T_c and ρ_c as our model B, but exhibited afterwards several pulsations and finally developed an iron core of 2.2 $M_\odot$. The reason why these computations differ from ours are not obvious yet. It could be partially related to the oxygen core mass being 43 $M_\odot$ in our model and 40 $M_\odot$ in Woosley and Weaver's model (Woosley, private communication). Another effect not yet included in our calculations may come from the Klein-Nishina temperature correction to electron scattering opacity, which results in a reduction of the Thomson scattering opacity (cf. Fuller and co-workers, 1986). We are currently investigating the effect of reduced opacities on our models.

IV. NUCLEOSYNTHETIC YIELD IN COMPARISON WITH CAS A

The optical observations of Cas A (Chevalier and Kirshner, 1979) show that the low-velocity knots of average velocity ~150 km/s contain H and enhanced He and N. These knots are interpreted as material originating from mass loss by stellar wind during the quasi-static evolution of the progenitor star. We have found (Langer and El Eid, 1986) that a wind-driven mass loss from a 100 $M_\odot$ star during hydrogen and helium burning can explained the observed overabundances of He and N in the low-velocity knots of Cas A.

One has also to seek for an explanation of the abundances observed in the fast moving knots (FMK) of Cas A. These have an average velocity of ~5000 km/s away from the center of the remnant, and show no H, He, or N emission, rather their compositions are inhomogeneous and dominated by oxygen and oxygen burning products S, Ar, and Ca. In Fig. 4 the observed (Chevalier and Kirshner, 1979) ratios by mass relative to oxygen for these elements in several FMKs are shown together with the final composition profiles obtained from our models. This comparison shows that the observed ratios are consistent with different layers in the stellar cores. The observed upper limit for C and Ne are found at the position where C-burning and Ne-burning have occurred. The upper limit for Mg is, however encountered deeper in the star, where the ratios for S, Ar, Ca are the natural result of oxygen burning. Fig. 4 shows also that the highest observed ratios for these elements result from oxygen burning near the center, where peak temperatures are achieved.

These results are actually expected from the nuclear physics aspect of oxygen burning, and can as well be obtained from the explosion of a 25 $M_\odot$ star as it has been shown by Johnston and Yahil (1984). However, these authors found that this type II explosion cannot account for the total production of the Si-rich material of Cas A, since only about 1% of the total mantel ejecta contain the abundances as observed in Cas A. This rises the difficulty of explaining the X-ray estimate (Fabian and co-workers, 1980) of the mass of the ejecta being higher than 15 $M_\odot$. In contrast, this difficulty is not encountered in our models, since the Si-rich layers comprise sufficient mass (see Fig. 4) to account for the X-ray observations without assuming efficient mixing during the explosion.

In order to place some constraints on the mass of the exploding WR star, we have compared (see EL Eid and Langer, 1986 for details) the calculated elemental abundances for the oxygen burning products with those inferred from the X-ray data (Becker and co-workers, 1979). Taking into account the uncertainties involved in these data, we found that our model B was in better agreement than model A. That means an exploding WR star by the pair creation instability as a

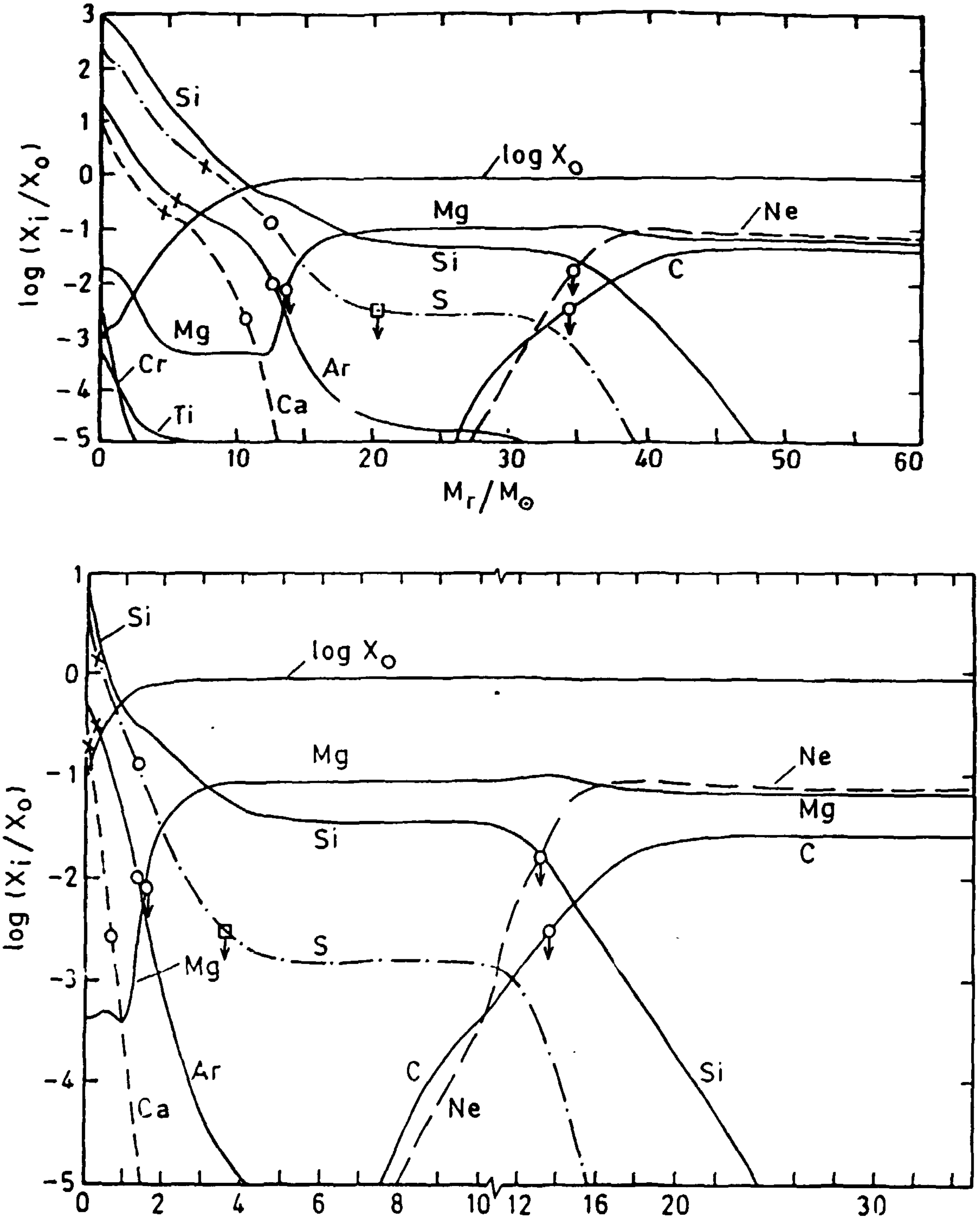

Fig. 4 Comparison of the observed abundance ratios relative to oxygen in the fast moving knots of Cas A with the calculated ones for model A (upper Fig.) and model B (lower Fig.). The observed ratios are those of Chevalier and Kirshner (1979) and their range is shown by using the superimposed data for the knots filament no. 1, 2F4 (open circles), KB33 (crosses), and [O III] filament (square for the element S). The arrows shown indicate upper limits inferred from the optical observations. The oxygen profile (log X_O) is plotted in addition.

progenitor of Cas A would have a mass not much higher than 45 $M_\odot$ and would evolve from a star of an initial mass of about 100 $M_\odot$.

It is interesting to note that recent observations of the supernova 1985f in NGC 4618 (Filippenko and Sargent, 1986), indicate that this object may have resulted from the explosion of a massive W-R star. Furthermore, Begelman and Zarasin (1986) proposed that SN 1985f is an example of the pair creation instability supernova and suggested a WR star of $\sim$ 50 $M_\odot$ as a progenitor.

In conclusion, the scenario for the exploding WR stars we have briefly described in this contribution seems to be an attractive model for the explanation of some of the oxygen-rich supernovae remnants.

ACKNOWLEDGEMENT

M.F.E. is grateful to the CNRS for supporting the traveling expenses to Erice, and he would like to thank Prof. J. Audouze for continuous encouragement. N.L. was supported by the Deutsche Forschungsgemeinschaft under grant no. FR 325/22-2.

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