Nucleosynthesis and Gamma Ray-Line Astronomy

Elisabeth Vangioni-Flam\textsuperscript{a}, Reuven Ramaty\textsuperscript{b} and Michel Cassé\textsuperscript{c}

\textsuperscript{a} Institut d'Astrophysique de Paris, 98bis Bd Arago 75014 Paris, France

\textsuperscript{b} GSFC, NASA, Greenbelt, MD 20771, USA

\textsuperscript{c} Service d’Astrophysique, CEA, Orme des Merisiers 91191 Gif/Yvette, France

The most energetic part of the electromagnetic spectrum bears the purest clues to the synthesis of atomic nuclei in the universe. The decay of radioactive species, synthesized in stellar environments and ejected into the interstellar medium, gives rise to specific gamma ray lines. The observations gathered up to now show evidence for radioactivities throughout the galactic disk, in young supernova remnants (Cas A, Vela), and in nearby extragalactic supernovae (SN 1987A, SN 1991T and SN 1998bu), in the form of specific gamma ray lines resulting, respectively, from the radioactive decay of $^{26}$Al, $^{44}$Ti and $^{56}$Co. The various astrophysical sites of thermal nucleosynthesis of the radioactive nuclei were discussed: AGB and Wolf-Rayet stars, novae, and type Ia and type II supernovae. Nuclear excitations by fast particles also produce gamma ray lines which have been observed in great detail from solar flares, and more hypothetically from active star forming regions where massive supernovae and WR stars abound. This non thermal process and its nucleosynthetic consequences was reviewed. The 511 keV line arising from $e^+ + e^-$ annihilation also provides important information on explosive nucleosynthesis, as well as on the nature of the interstellar medium where the positrons annihilate. INTEGRAL, the main mission devoted to high resolution nuclear spectroscopy, should lead to important progress in this field.

1. Observational status

The experimental situation in gamma ray line astronomy was summarized by G. Vedrenne. The highlights are: i) the discovery (1) of $^{44}$Ti emission from the Vela region (GRO JO852-4642) near a new supernova remnant detected in X rays by the ROSAT satellite (2); ii) the positive detection of a recent SNIa by COMPTEL (SN 1998bu) located at 8.1 Mpc (3); iii) the release of a new $^{26}$Al COMPTEL map derived from the observations using a sophisticated technique of data analysis (4);
iv) the withdrawal of the Orion gamma ray line data, followed immediately by the announcement of a similar emission from the Vela region (5). In addition, P. von Balmoos presented a review on the origin of galactic positrons, including compact galactic sources and radioactive nuclei ($^{26}$Al, $^{44}$Ti, $^{56}$Co).

2. Production of radioactive nuclei in thermal nucleosynthesis

2.1. Non explosive nucleosynthesis: AGB and Wolf-Rayet stars

G. Meynet analyzed the synthesis of $^{26}$Al in AGB and WR stars. Production in AGB stars falls short from explaining the required live radioactive aluminum in the galaxy (about $2M_\odot$), but WR stars remain a serious candidate. Indeed, the detailed analysis of the COMPTEL $^{26}$Al map and its correlation with the free-free emission of the galactic disk, as observed by COBE, indicates that massive stars are the most likely candidates for $^{26}$Al production (4). But at the moment, it is not possible to discriminate between core collapse supernovae and WR stars since neither the Vela SNR nor the $\gamma$ Velorum WR star coincide with peaks on the 1.8 MeV COMPTEL map. The absence of a clear detection signal implies that the progenitor of WR11 in Vela has a mass less than 40 $M_\odot$.

M. Arnould, broadening the scope, has pointed out the exceptional interest of radionuclide astrophysics at large, since it provides strong links between gamma ray astronomy, chemical evolution of the galaxy, stellar nucleosynthesis, and the physico-chemistry of circumstellar envelopes, the ISM, and the early solar system. After a critical analysis of all nucleosynthetic sites, he concluded that WR modeling is immensely simpler than that of AGB stars, novae and supernovae. He surmised that WR stars might be of interest to cosmochemists since they could provide a wealth of isotopic anomalies, potentially observable in meteorites.

2.2. Explosive nucleosynthesis

A. Core collapse supernovae and their remnants (SNII).

The nucleosynthesis of $^{26}$Al and $^{44}$Ti by core collapse was critically examined by F-K. Thielemann. Taking for example a 15 $M_\odot$ star, the $^{26}$Al yields of (6) and (7) differ significantly ($3\times10^{-8}$ against $2.7\times10^{-6}$ $M_\odot$). The origins of differences concern the choice of the still controversial $^{12}$C($\alpha$, $\gamma$)$^{16}$O reaction rate, and above all the treatment of convection (Schwarzschild or Ledoux + semi-convection, rotationally induced mixing and so on). Concerning the Fe-group elements, the variations between models are expected to be more acute due to a different simulation of the explosion, affecting the mass cut. Surprisingly, for the 15 $M_\odot$ model, the amounts of ejected $^{44}$Ti, $^{56}$Ni, $^{57}$Ni are similar in both cases (respectively $6\times10^{-5}$, 0.1 and $4\times10^{-3}$ $M_\odot$). However, the optimism should be tempered since the $^{44}$Ti yield varies a lot as a function of mass between the different authors. Anyway, using the new half-life determination (59-62 yr), the amounts of $^{44}$Ti ejected by SN 1987A (estimated from the late light curve, roughly $10^{-4}$ $M_\odot$), Cas A (about $1.3\times10^{-4}$ $M_\odot$ from gamma
rays) and JO852-4642 in Vela \((5\times10^{-5} \, M_\odot)\) can be explained with a calculation employing spherical symmetry. Concerning the synthesis of Fe, the main question is whether the mass of \(^{56}\text{Ni} (^{56}\text{Fe})\) ejected by core collapse supernova decreases or not as a function of the mass of the progenitor above \(20 \, M_\odot\). Light curve analyses that should help to solve this question are for the moment limited to the low mass range (less than \(30 \, M_\odot\)), unfortunately. So the question remains unsettled.

B. Thermonuclear supernovae (SNIa).

Type Ia supernovae are expected to produce greater quantities of \(^{56}\text{Ni}\) and to become transparent to gamma rays earlier than their gravitational counterparts of high masses (SNIa, SNIb, SNIc), as was discussed by S. Kumagai. Thus they are good targets of opportunity for gamma ray line astronomy. Indeed, an unusually bright SNIa (SN1991T), located at 13 - 17 Mpc, was already observed by COMPTEL at the edge of the Virgo cluster, close to the detection limit. The amount of ejected \(^{56}\text{Ni}\) derived from the observation (higher than 1 \(M_\odot\)) appears quite unusual, as does SN1991T itself. SN 1998bu, at a distance of 8.2 Mpc, presents certain similarities to SN 1991T. However, contrary to SN 1991T, the mean 847 keV line flux observed by COMPTEL from 5 to 131 days after the appearance of the supernova is somewhat low compared to the predictions of the models.

Concerning the observability of type Ia supernovae by INTEGRAL, S. Kumagai gave a mildly optimistic view. However, recent work \((8)\), that took into account the width of the 847 keV \(^{56}\text{Co}\) decay line, tempers this enthusiasm somewhat. If, by chance, an SNIa is captured by INTEGRAL in good conditions, the observation would help to calibrate the explosion models, the ejecta structure and the \(^{56}\text{Ni}\) distribution.

C. Novae

The best prospects are the lines resulting from \(^{7}\text{Be}\) and \(^{22}\text{Na}\) decays. None of these have been observed up to now. Only upper limits exist \((2\times10^{-8} \, M_\odot)\) on the ejected \(^{22}\text{Na}\) from neon rich novae. The GRO sky survey at 1.275 MeV gives only a marginal excess from South Aquila. M. Hernanz presented detailed nucleosynthesis calculations in nova explosions, employing hydrodynamical models for a variety of CO and ONe white dwarf masses. The low ejected mass of \(^{22}\text{Na}\) obtained in the ONe model is consistent with the observational upper limit. Only nearby novae should be captured by INTEGRAL, through the radioactive decay of \(^{7}\text{Be}\) (CO novae: 500 pc) and \(^{22}\text{Ne}\) (1.5 kpc, \((9)\)). In all models a strong continuum dominates the gamma ray spectrum during the early period of expansion. This short and intense emission could be detected at least up to 3 kpc, during a few hours \((10)\).

3. Non thermal gamma ray lines and associated nucleosynthesis

A broad overview of all aspects of gamma ray lines induced by non thermal particles in various astrophysical sites, including solar flares, was presented by R. Ramaty. The \(^{12}\text{C}\) and \(^{16}\text{O}\) lines, at 4.438 and 6.129 MeV, can only be produced by
non thermal particle interactions, a fact that can be used to distinguish a nonthermal from a nucleosynthetic origin of an observed gamma ray line spectrum. The \(^{12}\)C and \(^{16}\)O lines, as well as many others have been observed from solar flares. The most prominent ones are at 2.223 MeV following neutron capture on H, at 0.511 MeV from positron annihilation (both the neutrons and positrons results from nonthermal particle interactions), at 1.634 MeV from \(^{20}\)Ne and at 0.429 and 0.478 MeV from \(^{7}\)Be and \(^{7}\)Li produced in interactions of fast \(\alpha\) particles with He. These lines have provided much new information on particle acceleration as well as on the properties of the solar atmosphere (11, 12). With the withdrawal of the COMPTEL observations of the \(^{12}\)C and \(^{16}\)O lines from Orion, there remains no convincing evidence for such lines from non-solar sites. But the fast particles which produce the lines could have an important role in the origin of some of the light elements, in particular Be (13). This was the subject of a recent conference, the proceedings of which should appear shortly (see 14).

4. Conclusion

The COMPTON GRO mission has provided a wealth of data which has given a strong impetus to nuclear astrophysics. Now a new episode is opening up with INTEGRAL. In this context, F. Lebrun has shown the potential of the INTEGRAL satellite. The high quality spectroscopy of the SPI instrument, between 2 keV and 1 MeV, will shed light on fundamental questions of nucleosynthesis. Lines from \(^{44}\)Ti decay will be observed with both the SPI spectrometer and the IBIS imager. The proceedings of the invited talks and posters are available in the CDROM of the Texas Symposium.

REFERENCES

1. Iyudin, A.F. et al. 1998, Nature, 396, 142.
2. Aschenbach, B. 1998, Nature, 396, 141.
3. Leising, M.D. 1998 Third INTEGRAL Symposium, "The extreme Universe", Taormina, to be published.
4. Knodlseder, J. 1997, Thesis, Toulouse University.
5. van der Meulen, R.P. et al. 1998, Third INTEGRAL Symposium, "The Extreme Universe", Taormina, to be published.
6. Woosley, S.E. and Weaver, T.A. 1995, ApJS, 101, 181.
7. Thielemann, F.K. et al. 1996, ApJ, 460, 108.
8. Isern, J., 1998, Third INTEGRAL Symposium, "The Extreme Universe", Taormina, to be published.
9. Josés, J. and Hernanz, M. 1998, ApJ, 494, 680.
10. Gomez-Gomar J. et al. 1998, MNRAS, 296, 913.
11. Ramaty, R. et al. 1995, ApJ, 455, L193.
12. Mandzhavidze, N. et al. 1997, ApJ, 489, L99.
13. Vangioni-Flam et al. 1998, AA, 337, 714
14. Ramaty, R. et al. 1999, Publ. Astron. Soc. Pacific, in press).