A SHORT HISTORY OF GAMMA-RAY LINE ASTRONOMY

N. Prantzos
Institut d'Astrophysique de Paris

GAMMA-RAY LINES FROM YOUNG SUPERNOVA REMNANTS

DONALD D. CLAYTON*
Rice University, Houston, Texas

STIRLING A. COLGATE
New Mexico Institute of Mining and Technology, Socorro

AND

GERALD J. FISHMAN
Rice University, Houston, Texas

Received May 20, 1968; revised June 24, 1968

ABSTRACT

The gamma-ray luminosity of a typical type I supernova remnant has been calculated by assuming that the origin of the optical luminosity is due to the energy of the radioactive decay of Ni^{56}. It is expected that Ni^{56} is the most abundant nucleus resulting from silicon burning in the supernova shock conditions. The requisite mass of Ni^{56} (0.14 $M_\odot$) gives rise to gamma-ray lines with energies near 1 MeV that should be detectable in young supernova remnants at distances up to a few Mpc. Future detectors aboard satellites should be able to detect events at the rate of about two observable events per year. A few supernova remnants in the Galaxy should be observable at all times in lines following the decay of Ti^{44}.

Thus, the observation of gamma-ray line emission from a young supernova seems very promising in the near future. This observation, or even a null observation at a low threshold, will have great significance in the fields of nuclear astrophysics and supernova theory. The scientific importance of a positive measurement would be analogous with and comparable to the importance of the successful detection of neutrinos from the Sun.

1. Prehistory
1946 - 1968

Meteoritics & Planetary Science 34, A145–A160 (1999)

Radiogenic iron

DONALD D. CLAYTON

Clemson University, Clemson, South Carolina 29634-1911, USA
Author's e-mail address: clayton@gamma.phys.clemson.edu

(Received 1997 August 8; accepted in revised form 1998 June 25)

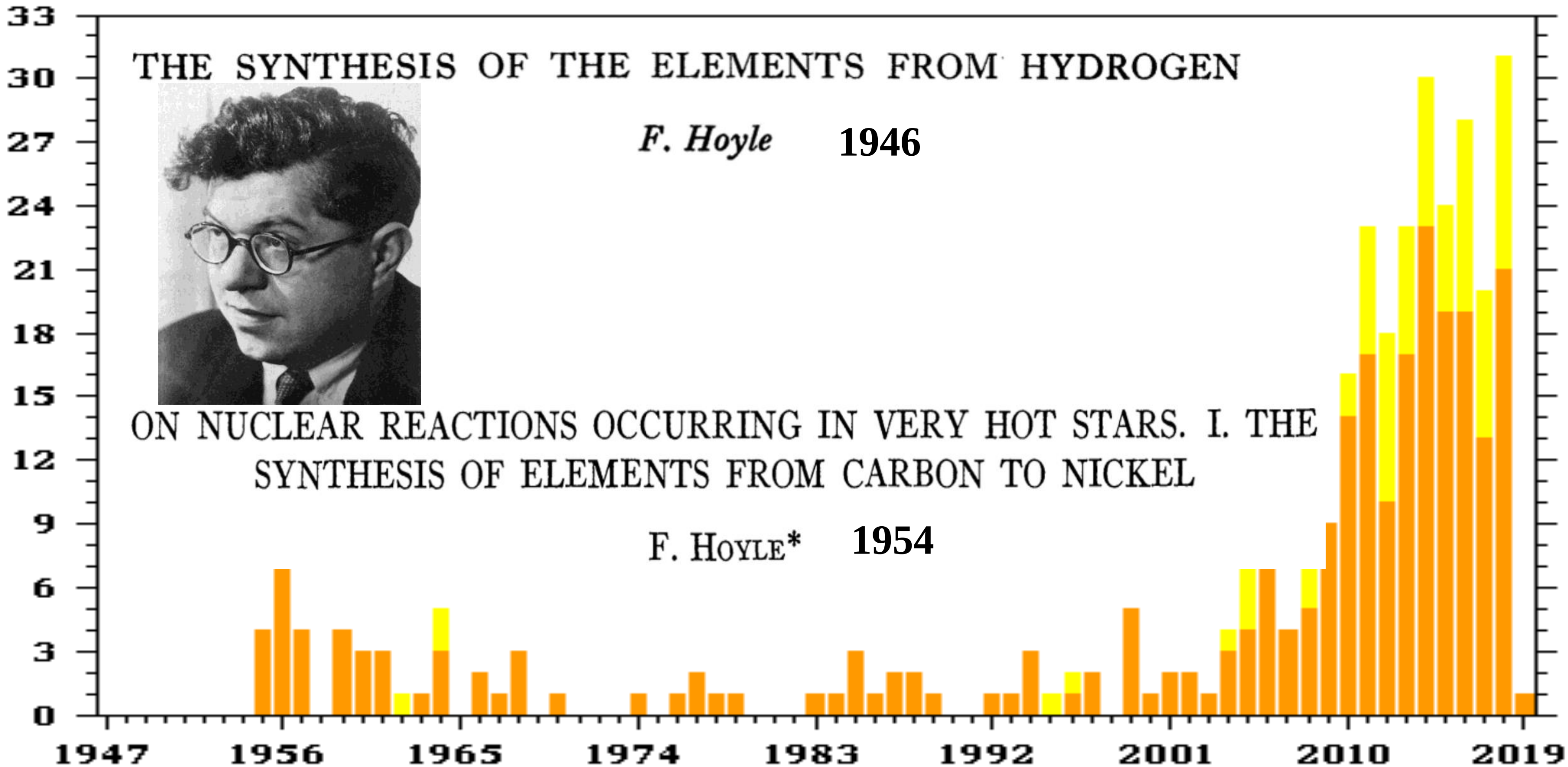
Abstract–This historical review focuses on the idea that this very abundant chemical element was overwhelmingly created and ejected from the stars not in its own chemical form but that of radioactive Ni progenitors. Iron in the universe outnumbers all of the common metals. Its thermonuclear origin provided the beginnings for the theory of nucleosynthesis in stars. Three of its isotopes (masses 54, 56, and 57) are counted among the most prominent isotopes of any element. Two of these isotopes (^{56}Fe and ^{57}Fe) are now known to have derived naturally from the radioactive decay of Ni isobars outside of exploding stars. Tension and numerous mistakes surrounding the discovery of its radiogenic origin are analyzed with historical accuracy. The radioactive origin is described as having been first overlooked and later resisted to considerable degree. But incontrovertible evidence, especially from supernova light curves and gamma-ray-line astronomy, has established its correctness. Radiogenic Fe thus remains the centerpiece for both the theory and the observations of nucleosynthesis in stars.

2. History
1969 - 2019

Chapter 2
The Role of Radioactive Isotopes in Astrophysics

Donald D. Clayton

Astrophysics with Radioactive Isotopes
Eds. R. Diehl, D. Hartmann, NP
(Spinger 2018, 2nd Edition)



Fe56 is made as Fe56, in its stable form

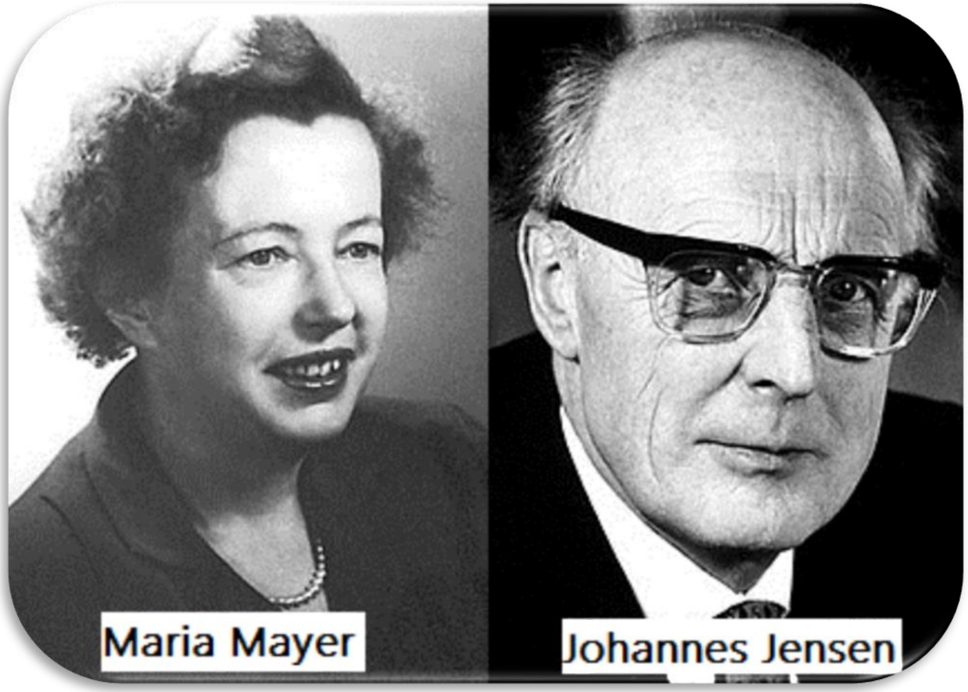
ABUNDANCE RATIOS RELATIVE TO Fe^{56} (LOGARITHMS TO BASE 10)

	Nucleus									
	Ti^{48}	Cr^{52}	Fe^{54}	Mn^{55}	Fe^{57}	Fe^{58}	Ni^{58}	Co^{59}	Ni^{60}	Ni^{62}
Theoretical abundances.........	−3.3	−0.38	−0.47	−2.3	−2.3	−2.0	−1.5	−2.6	−0.67	−3.1
Meteoritic abundances.........	−2.6	−1.9	−1.2	−2.0	−1.6	−2.5	−1.8	−2.4	−1.4	−2.7

1963 Physics Nobel Prize

½ to
Maria Goeppert-Mayer
and
Johannes Jensen

for Shell model of nucleus



J. Jensen with
Hans Suess and Otto Haxel

1946-1947: Haxel suggests that Fe56 is made as unstable Ni56

based on the property of Ni56 of being a « double-magic » nucleus

REVIEWS OF MODERN PHYSICS VOLUME 28, NUMBER 1 JANUARY, 1956

Abundances of the Elements*

HANS E. SUESS,† *U. S. Geological Survey, Washington, D. C.*

AND

HAROLD C. UREY, *Department of Chemistry and Enrico Fermi Institute for Nuclear St*
University of Chicago, Chicago, Illinois

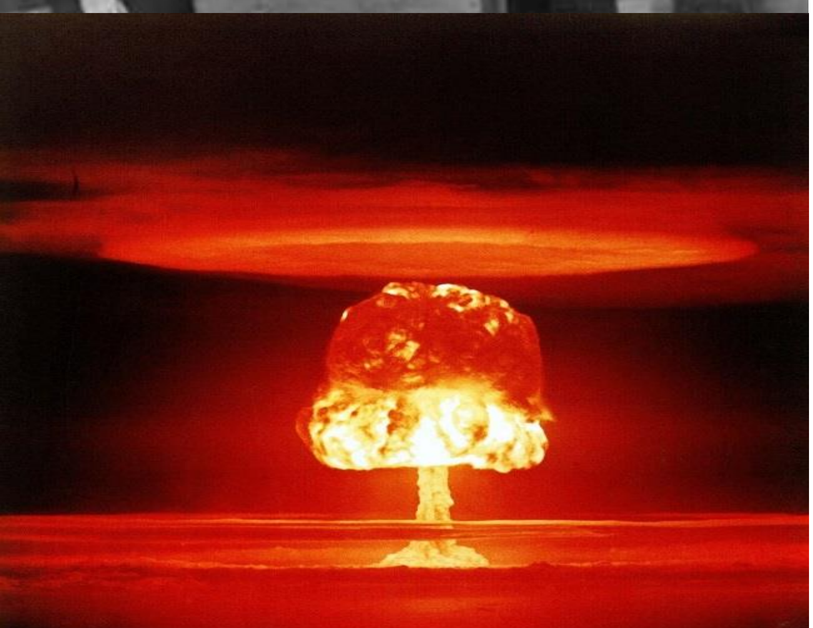
The Iron Peak and the Lower Mass Region

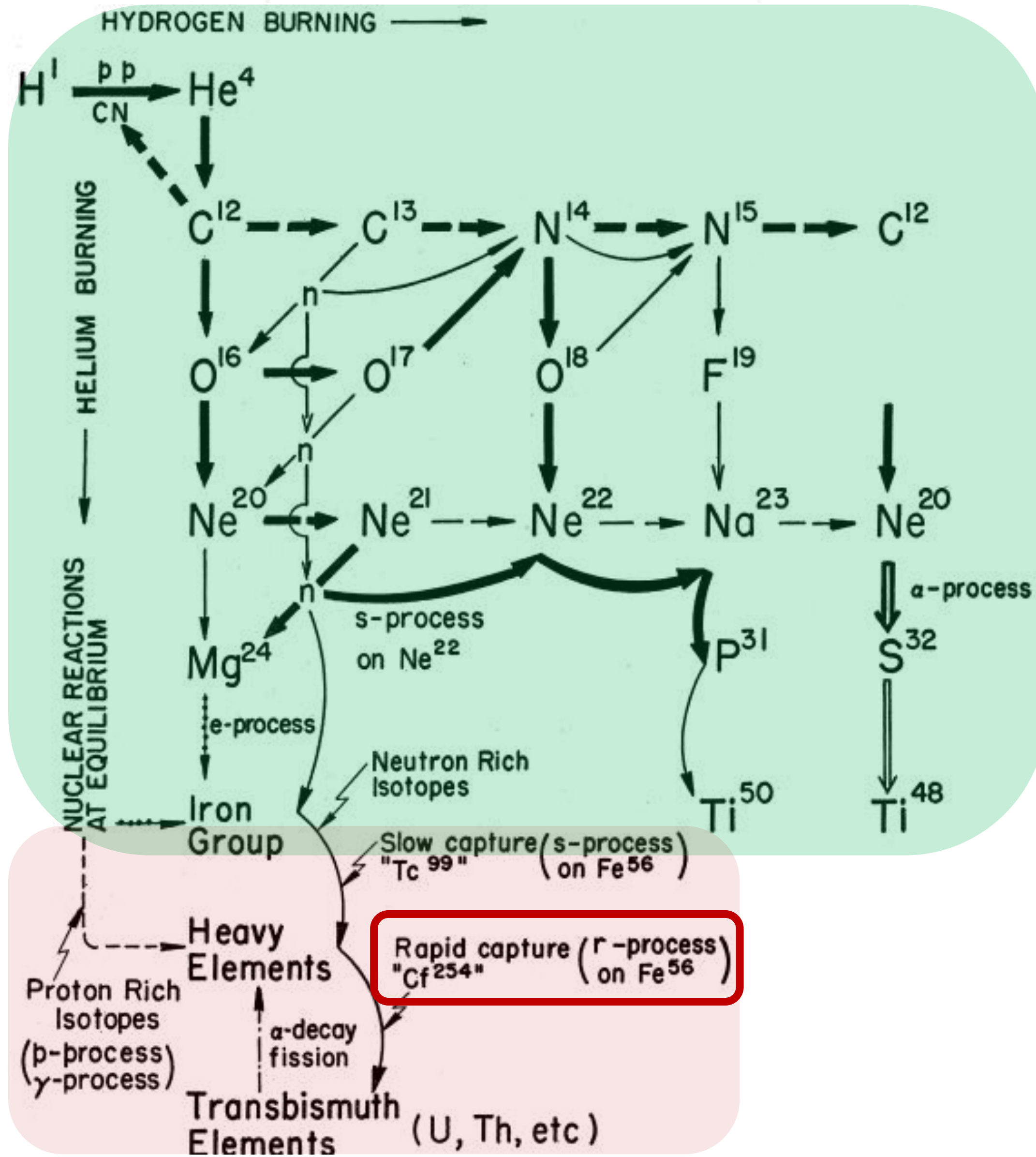
The new value for the Fe to Si ratio, which is about one third of that previously assumed, still leaves the abundance of Fe^{56} larger than the sum of abundance of all other nuclear species with mass numbers greater than 40. No property of the Fe^{56} nucleus is known that could possibly explain its predominance in nature. Fe^{56}, however, is an isobar of the "double magic" unstable Ni^{56}, which contains 28 protons and 28 neutrons. The expectation of a correlation of abundances with nuclear properties leads inevitably to the conclusion that Ni^{56} was the primeval nucleus from which Fe^{56} has formed|| and, hence, that the nuclei of this mass region had formed on the neutron deficient side of the energy valley. The half-life of Ni^{56}, which decays by *K*-capture into Co^{56} (80d) has recently been found to be 6.5 days [Sheline and Stoughton (1952) and Worthington (1952)]. Hence the process leading to the excessive abundance of mass 56 cannot have taken longer than a few days.

Reviews of Modern Physics 1957

Synthesis of the Elements in Stars*

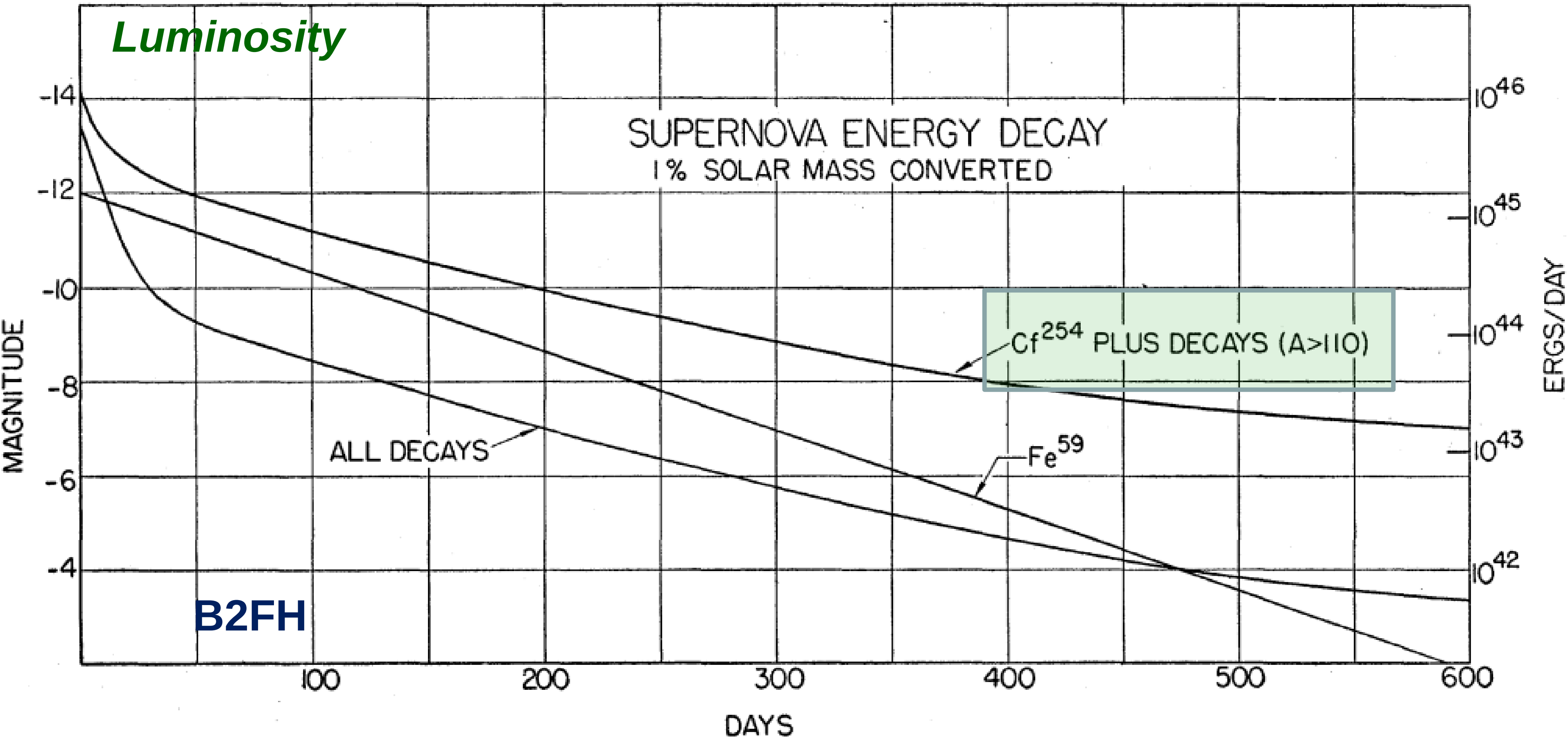
E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle





The recent analysis of the atomic abundances (Su56) has enabled us to separate the isotopes in a reasonable scheme depending on which mode of synthesis is demanded. In particular, the identification of the *r*-process peaks was followed by the separation of the heavy isotopes beyond iron into the *s*-, *r*-, and *p*-process isotopes, and has enabled us to bring some order into the chaos of details of the abundance curve in this region. The identification of Cf^{254} in the Bikini test and then in the supernova in IC 4182 first suggested that here was the seat of the *r*-process production. Whether this finally turns out to be correct will depend both on further work on the Cf^{254} fission half-life and on further studies of supernova light curves, but that a stellar explosion of some sort is the seat of *r*-process production there seems to be little doubt.

What powers the exponentially decreasing lightcurves of supernovae ?



R a d i o a c t i v i t y, lifetime ~2 months

Be-7 : Borst 1950

Cf-254: Baade, B2FH, and Christy 1956

Hoyle and Fowler 1960
Explosive nucleosynthesis

The role of Type I and Type II supernovae in nucleosynthesis is treated in some detail. It is concluded that e-process formation of the iron-group elements takes place in Type II supernovae, while r-process formation of the neutron-rich isotopes of the heavy elements takes place in Type I supernovae. The explosion of Type II supernovae is shown to follow implosion of the non-degenerate core material. The explosion of Type I supernovae results from the ignition of degenerate nuclear fuel in stellar material.

We have considerable confidence in our order-of-magnitude estimates of the production of fissionable material in Type I supernova explosions. The input of radioactive energy into the exploding debris of supernovae cannot be neglected. Furthermore, the production of Cf254 within an interval of a few microseconds in the first hydrogen bomb test in 1952 must be taken as observational evidence for the rapid process of neutron capture, by which fissionable material is produced in supernova explosions. The heaviest nucleus in the bomb components was U238 . At least 16 neutrons were added in the short interval of the bomb explosion. It is not unreasonable to extrapolate by a factor of 10 or more in going to stellar explosions, where the iron-group elements serve as seed nuclei but the neutron fluxes are considerably enhanced.

TITUS PANKEY, JR.* 1962

Department of Physics and Astronomy, Howard University

Received 1980 March 24, revised 1980 June 16

Two decades ago (Pankey 1962, 1963), it was suggested that during type-I supernova eruptions a resonant fusion of two Si^{28} nuclei, followed by the beta decay of Ni^{56} and Co^{56} to Fe^{56}, would explain the characteristic features of the luminosity curve (Fig. 1):

Pankey, T., Jr. 1962, *Dissertation Abstracts* 23, No. 4, 1395.

——1963, *Nuclear Science Abstracts* 17, No. 4, 606.

NUCLEAR QUASI-EQUILIBRIUM DURING SILICON BURNING*

DAVID BODANSKY†
University of Washington, Seattle, and California Institute of Technology, Pasadena

DONALD D. CLAYTON‡
Rice University, Houston, Texas, and Institute of Theoretical Astronomy, Cambridge, England

AND

WILLIAM A. FOWLER
California Institute of Technology, Pasadena, and Institute of Theoretical Astronomy, Cambridge, England

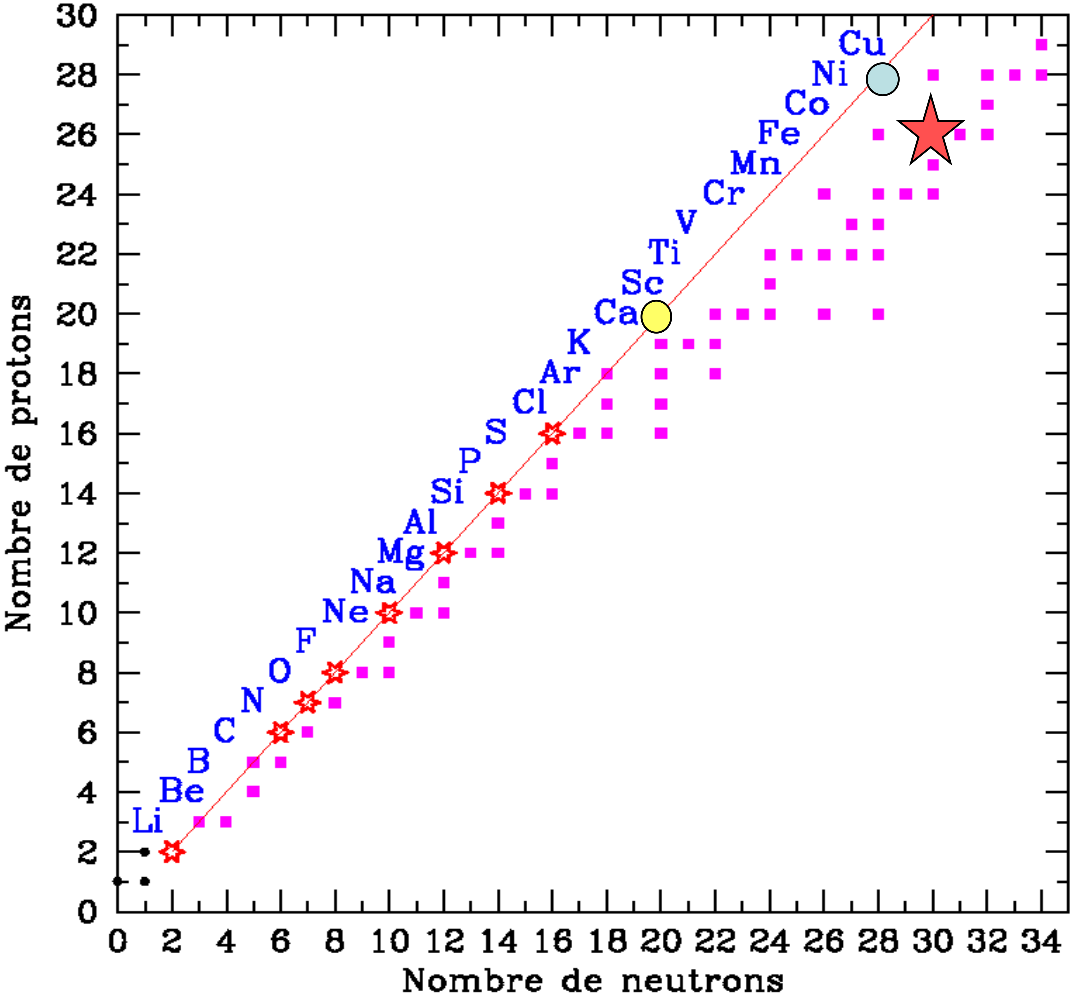
Received February 23, 1968

The distinctive conclusions of the present analysis are the following: (1) the synthesis of the alpha-particle nuclei and the synthesis of the iron-group nuclei occur simultaneously in silicon burning (to be explicit, the *α*-process and the *e*-process of Burbidge *et al*. and Fowler and Hoyle occur simultaneously); (2) the chief equilibrium product in the iron group is ^{56}Ni, the decay to ^{56}Fe occurring after the termination of the quasi-equilibrium silicon burning; and (3) under the most likely conditions, the production of the iron-group nuclei in silicon burning is accompanied by a large release of nuclear energy.

Supernovae are powered by the radioactivity of Ni56 decaying to Fe56

Ni56 → Co56 → Fe56

The way towards the Fe-peak



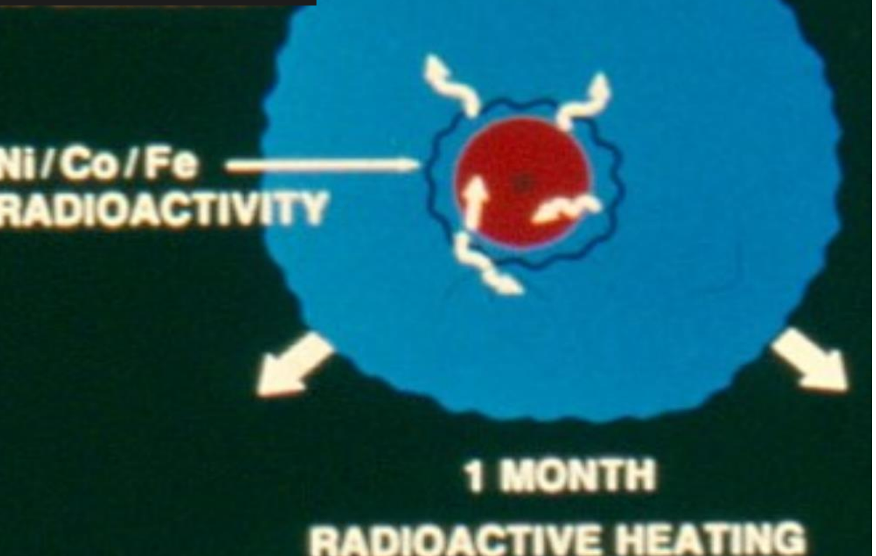
Ca40 is the last stable nucleus with N=Z=20 on the way of Si-melting towards the Fe-peak

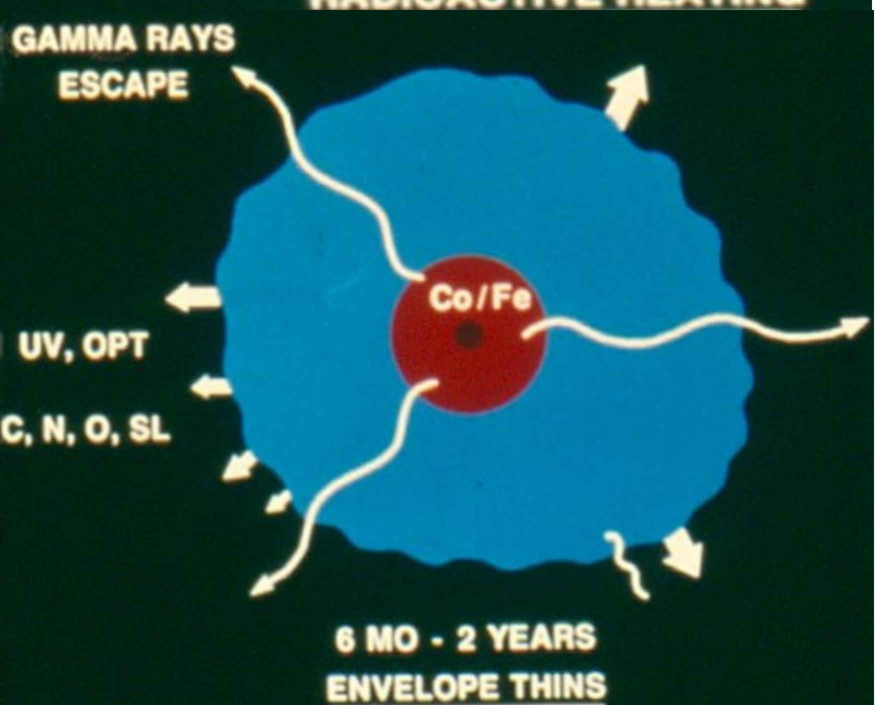
In the stellar core weak interactions ($p + e^+$) turn some protons into neutrons and Fe56 dominates the composition in nuclear statistical equilibrium

In explosive nucleosynthesis, weak (=slow) interactions have no time to operate and the nuclear flow goes through N = Z up to Ni56 (N=Z=28)

Hoyle's greatest regret : missing the origin of Fe56, the most stable nucleus in nature
It is produced as unstable Ni56 in supernova explosions

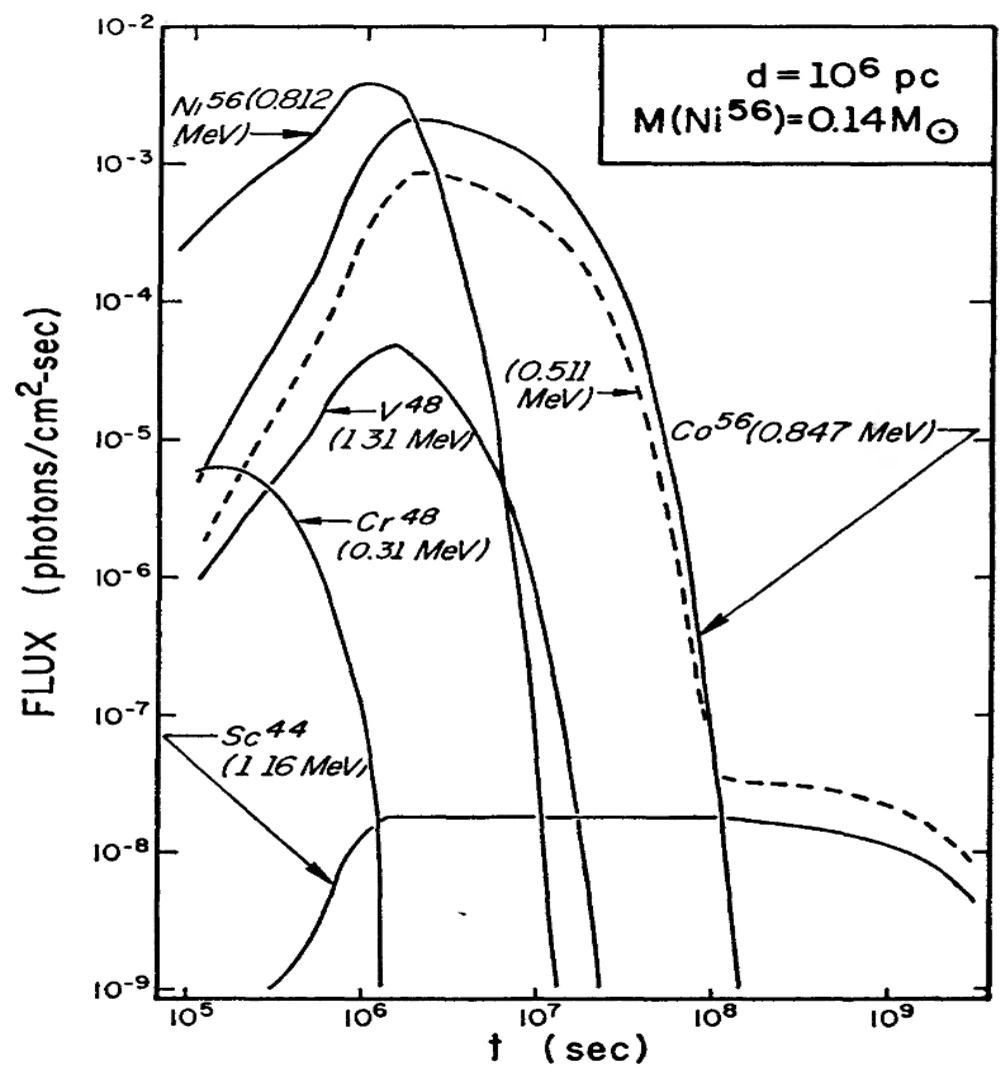
EXPANDING SN



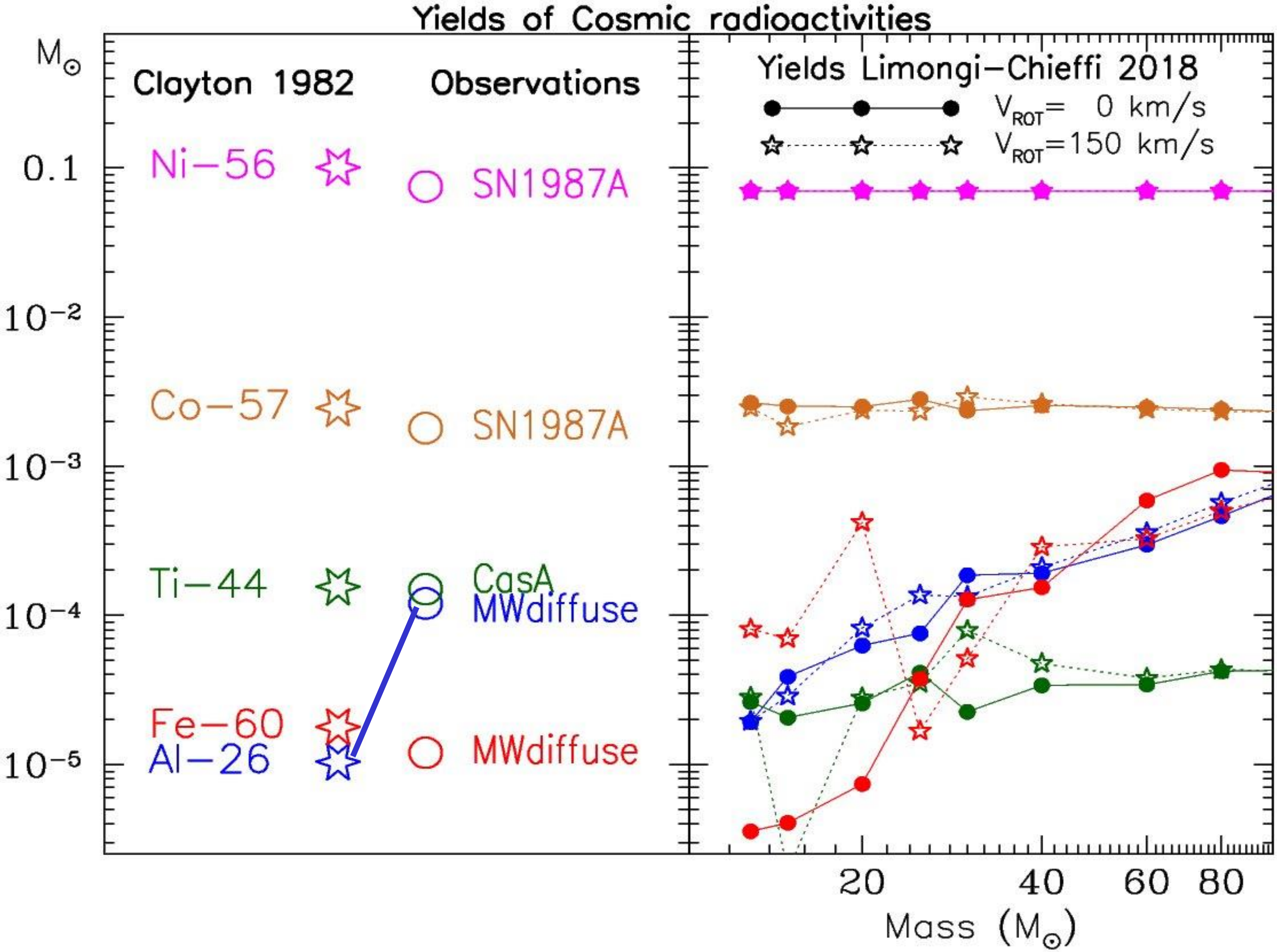


Clayton, Colgate and Fishman 1969

Gamma-ray lines from young supernova remnants



Assuming that the corresponding stable nuclei are produced at their Solar system abundances



DIFFUSE GALACTIC GAMMA-RAY LINE EMISSION FROM NUCLEOSYNTHETIC ^{60}Fe, ^{26}Al, AND ^{22}Na: PRELIMINARY LIMITS FROM *HEAO 3*

W. A. MAHONEY, J. C. LING, AND A. S. JACOBSON
Jet Propulsion Laboratory, California Institute of Technology

AND

R. E. LINGENFELTER
Center for Astrophysics and Space Science, University of California, San Diego
Received 1982 April 5; accepted 1982 May 18

^{26}Al IN THE INTERSTELLAR MEDIUM

DONALD D. CLAYTON

Max-Planck-Institut für Kernphysik, Heidelberg; and Rice University, Houston
Received 1983 July 25; accepted 1983 October 17

ABSTRACT

The amount of dispersed interstellar ^{26}Al detected by the *HEAO 3* γ-ray spectrometer cannot have been synthesized by supernova explosions if current calculations of the production ratio $p(26)/p(27) \approx 1 \times 10^{-3}$ are correct. Simple models of chemical evolution of the Galaxy are presented to explain this point. The observed ^{26}Al is more likely due to about 10^8 dispersed novae, or to a single old (10^4–10^6 yr) supernova remnant that today surrounds the solar system. If the ^{26}Al is dispersed, the high interstellar ratio today ^{26}Al/^{27}Al $\approx 2 \times 10^{-5}$ calls

stardust, I had discounted the chance of its astronomical detectability because its yield in primary nucleosynthesis was argued by me to be too small (Clayton, 1984). However, I had failed to see that it would be the secondary nucleosynthesis of ^{26}Al by (p, γ) reactions with initial ^{25}Mg in the shells of massive stars that would be responsible for its detectable ISM abundance. Ramaty and Lingenfelter (Ramaty and Lingenfelter, 1977) had no such reticence in suggesting that the 1.81 MeV line be sought. Even so, understanding the surprisingly large ^{26}Al interstellar abundance required an improved theory of galactic chemical evolution in order to understand (Clayton et al., 1993) why the present interstellar ^{26}Al/^{27}Al ratio should be a factor $(k+1)$=4–5 larger owing to past galactic infall of low-metallicity gas than it would have been in a closed-box model. I have always seen irony in secondary nucleosynthesis producing the first measurable interstellar concentration of a radioactive nucleus, and somewhat foolish for discounting it on incomplete theoretical grounds.

ROPHYSICAL JOURNAL, 321:761–767, 1987 October 15

THE PRODUCTION OF ^{26}Al IN SUPERMASSIVE STARS AND THE GAMMA-RAY LINE FLUX FROM THE GALACTIC CENTER

WOLFGANG HILLEBRANDT,[1] FRIEDRICH-KARL THIELEMANN,[2] AND NORBERT LANGER[3]

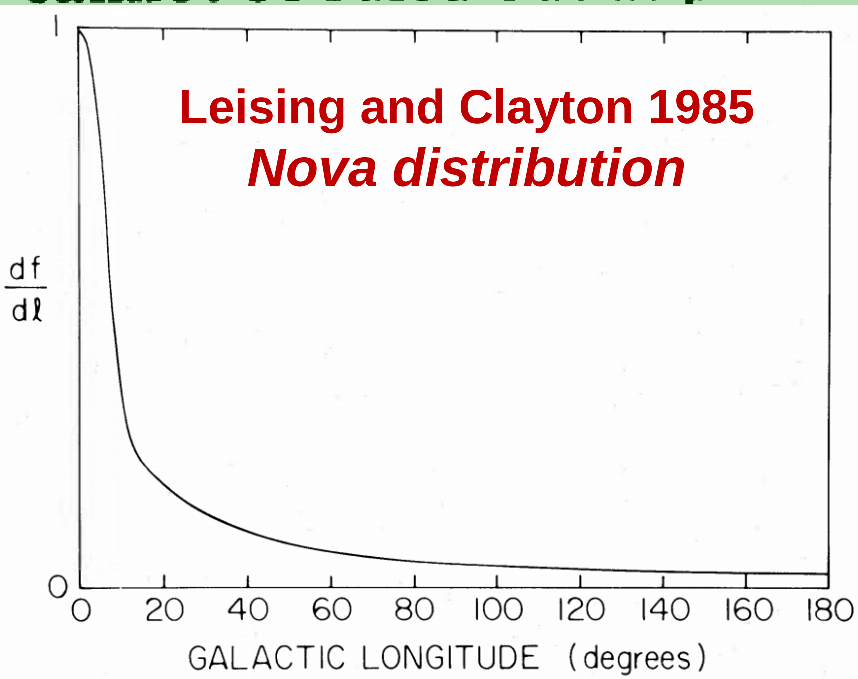
Received 1986 November 24; accepted 1987 April 6

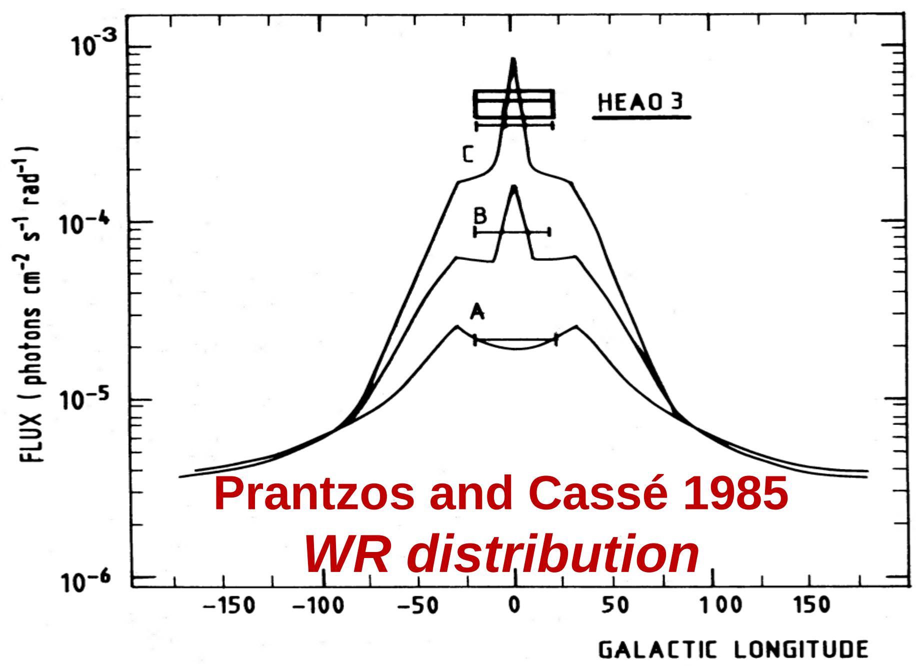
ABSTRACT

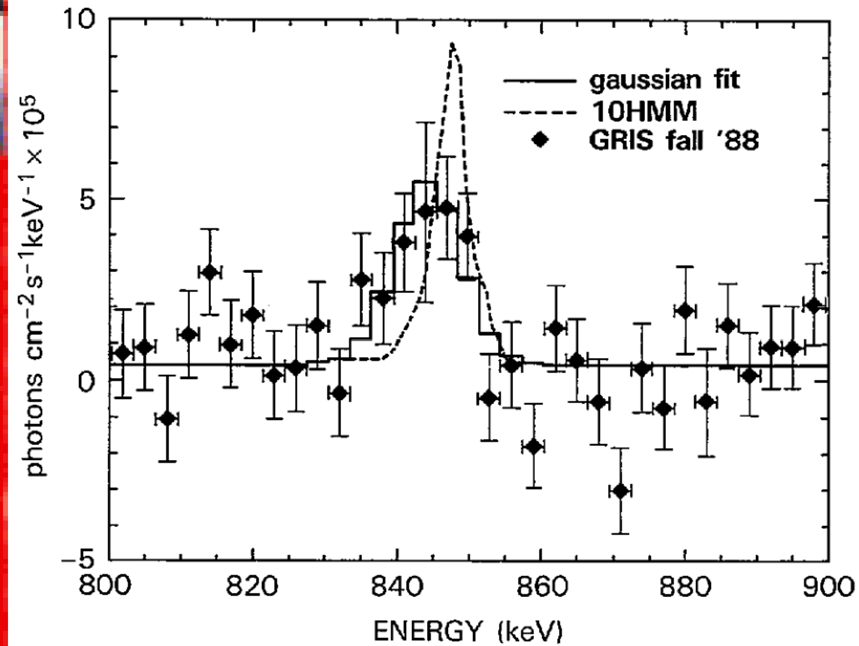
The evolution through contraction and explosion of a high-metallicity ($Z = 0.04$) supermassive star of $5 \times 10^5\ M_\odot$ is computed. It is shown that in the inner 20% of the star a significant fraction of the preexisting magnesium is converted into ^{26}Al leading to the production of about 50 $M_\odot$ of ^{26}Al. This amount is sufficient to explain the observed 1.8 MeV γ-ray line flux from the Galactic center if such a supermassive star exploded there within the last 2 million years. The ejecta will be enriched in the isotopes ^{13}C and ^{17}O, but with the exception of lithium and nitrogen all elements are produced in roughly solar relative proportions.

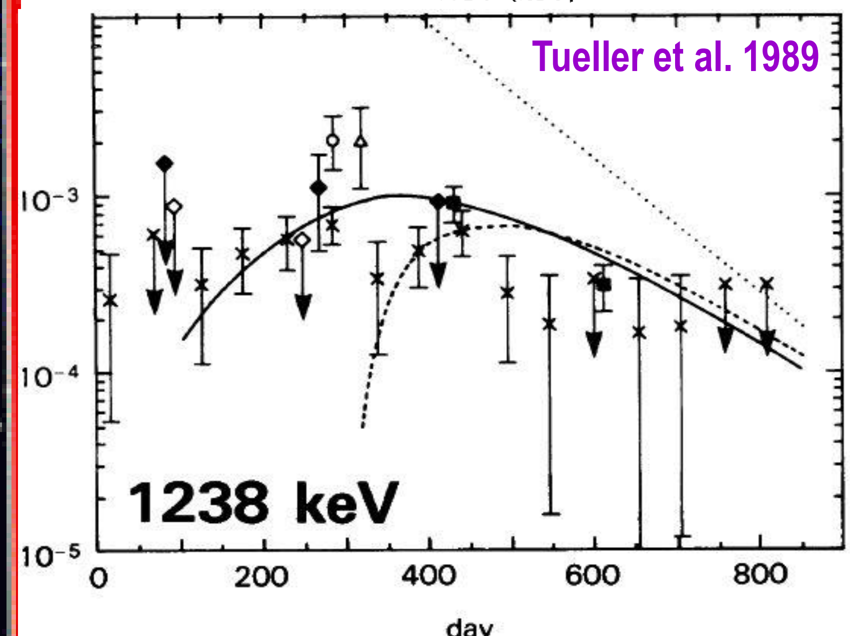
Recently, Ballmoos, Diehl, and Schönfelder (1987) have measured the intensity distribution of the 1.8 MeV line from the Galactic center region by using the Max-Planck-Institut (MPI) Compton telescope on a balloon flight. They observed a line intensity similar to, though somewhat higher than, what had been found by Mahoney *et al.* but concluded that their observations were fitted best by a "point source" of $5 \pm 2\ M_\odot$ of ^{26}Al at or near the Galactic center, the 1 σ angular resolution of their telescope being 3°.5. Although the statistical accuracy of the MPI measurement is not sufficient to exclude a diffuse origin of the γ-ray line flux, and data inconsistent with the MPI results have been reported (MacCallum *et al.* 1987), it cannot be ruled out at present that the galactic ^{26}Al is concentrated in a region of a few hundred pc close to or at the Galactic center.

Hydrogen-burning scenarios, on the other hand, in which ^{26}Al is synthesized from preexisting ^{24}Mg and ^{25}Mg by proton captures and β^+-decays (Arnould *et al.* 1980; Wallace and Woosley 1981: Hillebrandt and Thielemann 1982; Dearborn and Blake 1985; Prantzos and Cassé 1986: Wiescher *et al.* 1986) are more promising candidates. Again, the yields predicted by standard models are too small by a significant factor (Clayton 1984; Leising and Clayton 1985, Clayton and Leising 1987), but since the Mg abundance may be significantly higher toward the Galactic center, a large number of novae may escape detection (Clayton 1984) or the distribution of Wolf-Rayet stars may be strongly peaked near the Galactic center (Prantzos *et al.* 1985); these explanations face difficulties but cannot be ruled out at present.







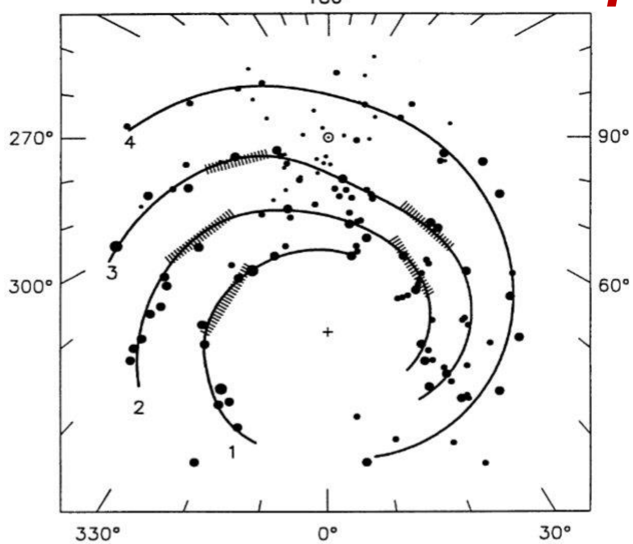


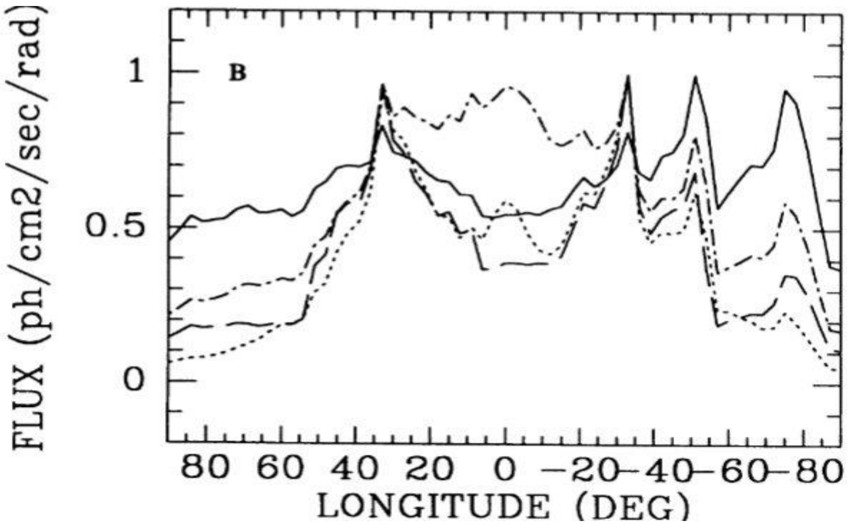
Line seen 6 months earlier than expected !

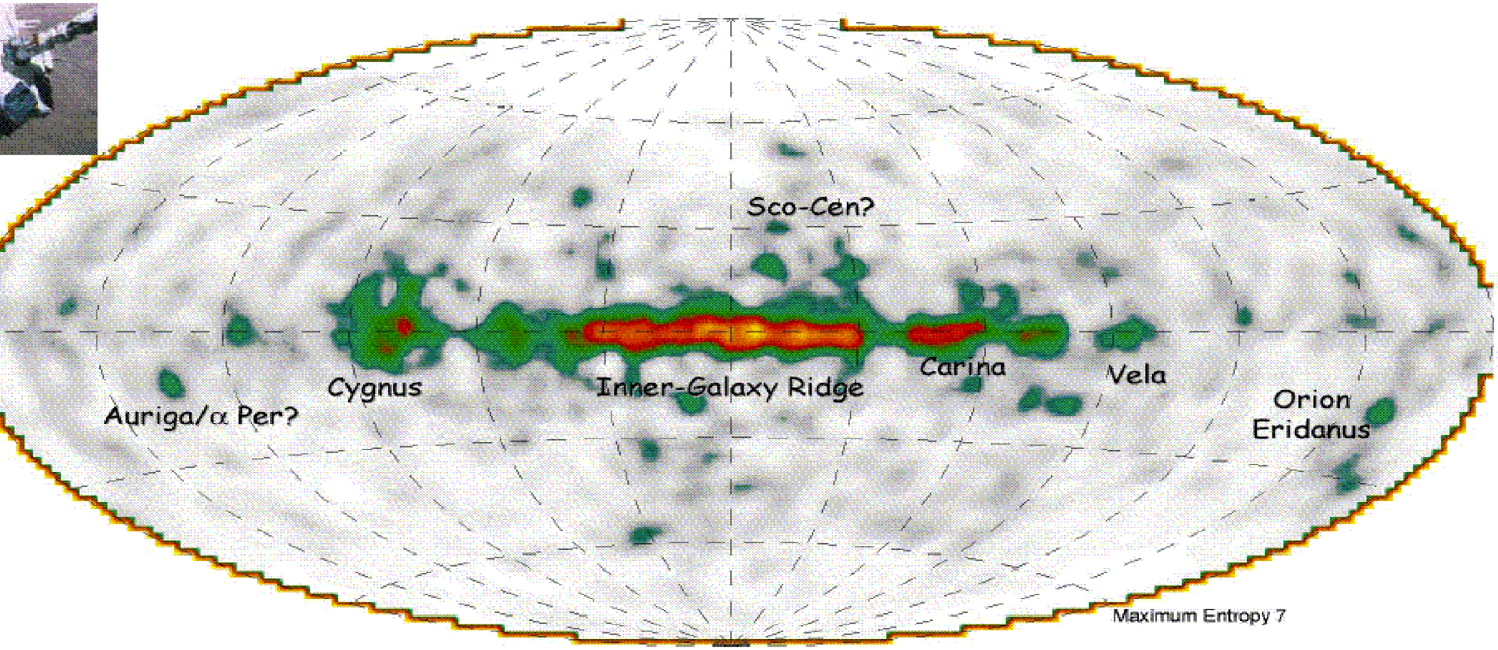
Gamma – ray line astrophysics

Saclay, France, December 1990

NP 1990, 1993: *IF massive stars at the origin of Al26: then « Hotspots » in spiral arm tangents*

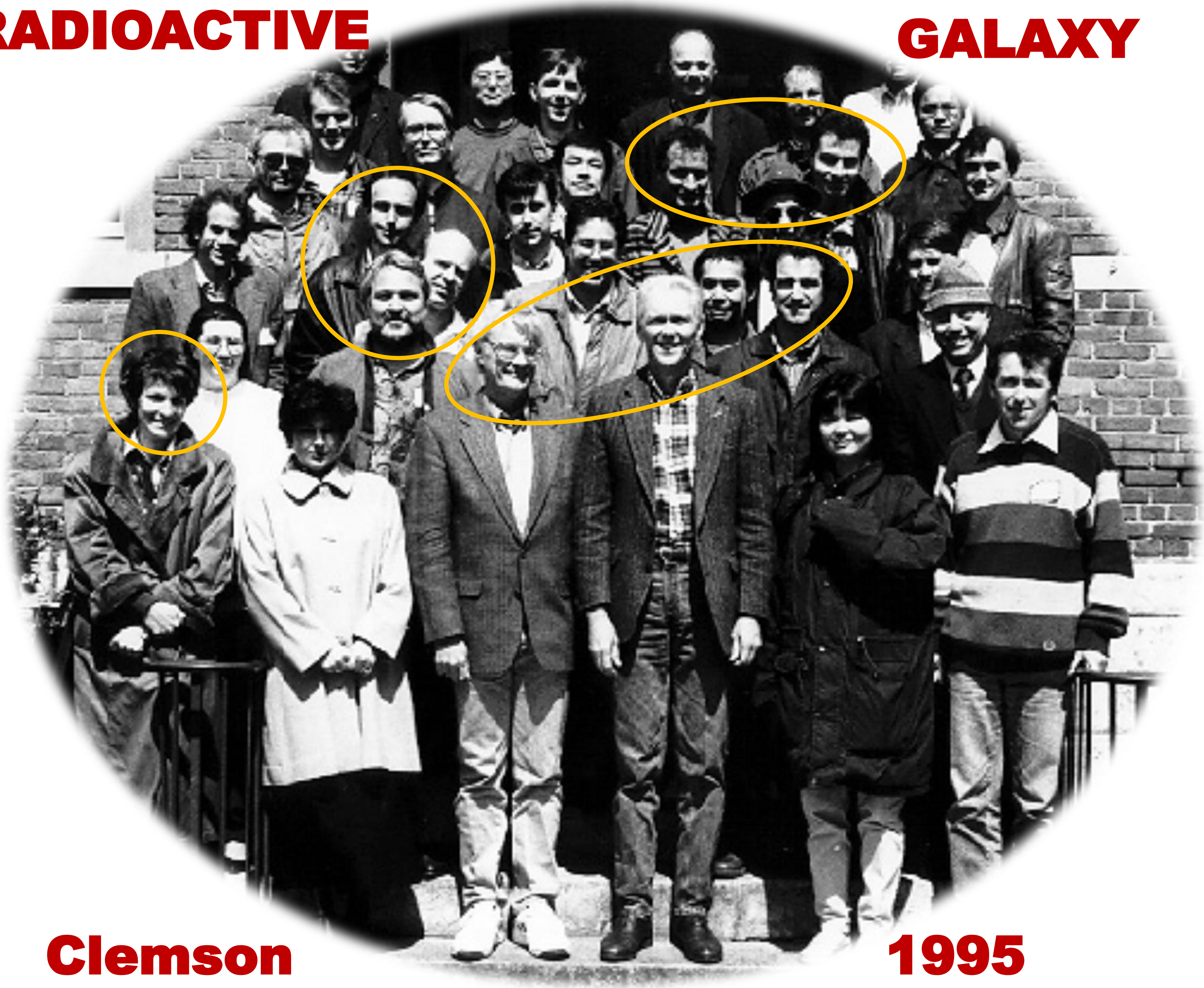






Complete CGRO Mission
(Plüschke et al. 2001)

RADIOACTIVE GALAXY



Clemson 1995


CLEMSON 1995

Astronomy with Radioactivities

I (Clemson, USA, 1995)

II (Ringberg, Germany, 1999)

III (Ringberg, Germany, 2001)

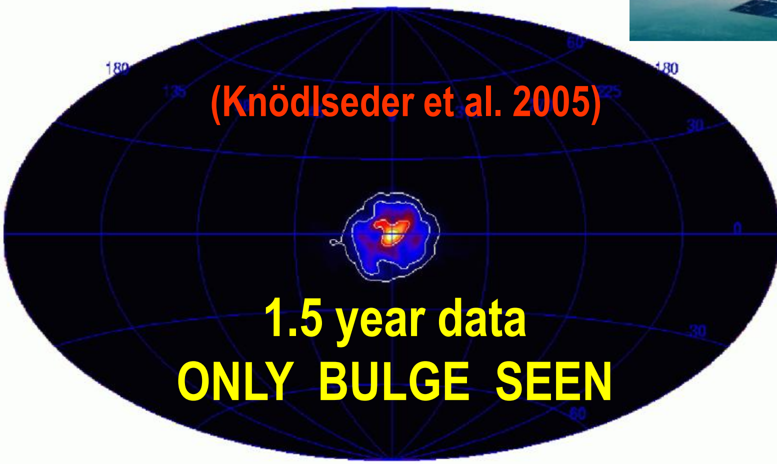
IV (Seeon, Germany, 2003)

V (Clemson, USA, 2005)

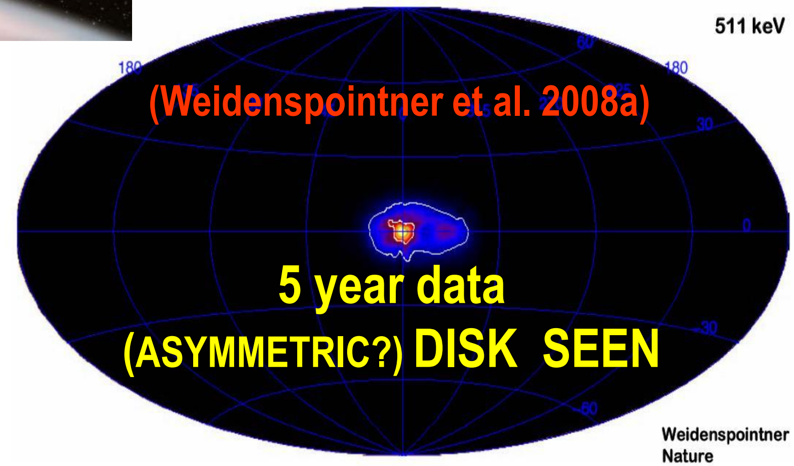
VI (Ringberg, Germany, 2008)

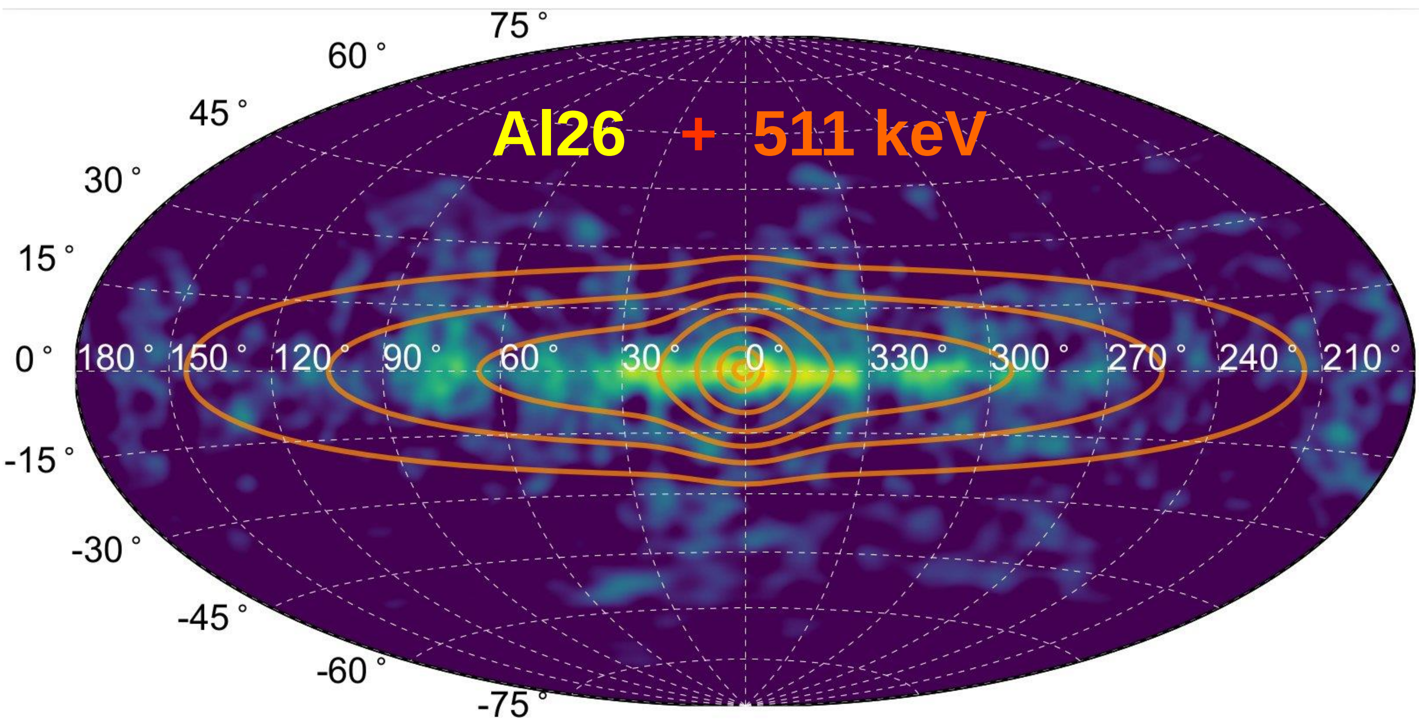
VII (Phillip Island, Australia, 2011)


CLEMSON 2005



SPI / INTEGRAL
all-sky
distribution
of the 511 keV
line of $e^- - e^+$
annihilation





Roland Diehl
Dieter H. Hartman
Nikos Prantzos
Editors
LECTURE NOTES IN PHYSICS 8
Astronomy
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hysics and Space Science Library 453
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Springer
2018
Astrophysics with Radioactive Isotopes

Biggest SCIENTIFIC blunders

Albert E. : Cosmological constant

Fred H. : Missing radiogenic Fe

Donald C. : Missing importance AND source of Al26

Roland D. : ????????????????????

COSMIC RADIOACTIVITIES AND GAMMA-RAY LINE ASTRONOMY

- 1946/1954: F. Hoyle: Fe56 made as stable Fe56
- 1946 : O. Haxel: Fe56 is made as radioactive Ni56
- 1956 : W. Baade, B2FH : Supernovae powered by decay of ^{254}Cf ($\tau_{1/2}$ = 70 days)
- 1964 : F. Hoyle + W. Fowler : ^{56}Fe is produced as stable ^{56}Fe
- 1962 : T. Pankey Jr. : Supernovae powered by decay of ^{56}Ni=> ^{56}Co ($\tau_{1//2}$= 77 days)
- 1968 : J. Bodansky + D. Clayton + W. Fowler : ^{56}Fe is produced as ^{56}Ni (unstable)
- 1969 : D. Clayton +S. Colgate + J. Fishman : Gamma-rays from ^{56}Co in SN detectable
- 1970ies : D. Clayton : Evaluation of yields of major radionuclides assuming that Supernovae make the solar abundances of the daughter stable isotopes. *ALL CORRECT* ! But : ^{26}Al missed ! (^{26}Mg is produced in stable form)
- 1977 : D. Arnett, R. Ramaty : ^{26}Al from SN explosions may also be detectable

- 1970's: Balloons : Discovery of 511 keV line towards Galactic Center
- 1984 : HEAO-3 (NASA) : Discovery of ^{26}Al towards Galactic Center
- 1987 : SMM + Balloons : Discovery of ^{56}Co in SN1987A
- 1990s : GRO (NASA) : Discovery of ^{57}Co (SN1987A), mapping of ^{26}Al (Galaxy), ^{44}Ti (Cas-A), 511 keV (Bulge+Disk ?)

2000s : INTEGRAL(ESA) : ^{60}Fe (Galaxy), Mapping of 511 keV (Bulge+Disk)