NASA TECHNICAL MEMORANDUM

NASA TM X-64722

THE ATTENUATION OF X RAYS EMITTED BY SUPERNOVAE

By Klaus Schocken
Space Sciences Laboratory

March 1973

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
NASA TM X-64722		

4. TITLE AND SUBTITLE
The Attenuation of X Rays Emitted by Supernovae

5. REPORT DATE
March 1973

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Klaus Schocken

8. PERFORMING ORGANIZATION REPORT #

9. PERFORMING ORGANIZATION NAME AND ADDRESS
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
National Aeronautics and Space Administration
Washington, D. C. 20546

13. TYPE OF REPORT & PERIOD COVERED
Technical Memorandum

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
Prepared by Space Sciences Laboratory, Science and Engineering

16. ABSTRACT

The attenuation of X rays in Arnett's C^{12} detonation supernova model is computed. The attenuation of X rays in the filaments of the Crab Nebula is computed using a model for the filaments by Woltjer and a model by Davidson and Tucker. An empirical expression by Gorenstein, Kellogg, and Gursky for the optical thickness of the interstellar medium for three supernova remnants is analyzed.

17. KEY WORDS
Crab Nebula
Supernovae Remnants
X Rays

18. DISTRIBUTION STATEMENT
Unclassified - unlimited
Klaus Schocken

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	12	NTIS

MSFC - Form 3292 (Rev December 1972)

For sale by National Technical Information Service, Springfield, Virginia 22151

TABLE OF CONTENTS

LIST OF TABLES

TECHNICAL MEMORANDUM X-64722

THE ATTENUATION OF X RAYS EMITTED BY SUPERNOVAE

I. INTRODUCTION

Using some of the models of supernovae which have been published, it is possible to compute the attenuation coefficients of the plasma immediately after the explosion and after transparency has been established, and to evaluate the attenuation in the interstellar medium of the X radiation of supernova remnants.

II. THE ATTENUATION OF X RAYS IN THE C^{12} DETONATION SUPERNOVA MODEL

The most complete theoretical model of a supernova explosion that has been published up to the present time is the one by Arnett, Truran, and Woosley (ATW) [1]. In this model, stars of intermediate mass ($4M_{\odot} \leqq M \leqq 9M_{\odot}$) ignite the $C^{12} + C^{12}$ reaction explosively. The star is totally disrupted. In the region interior to the helium-burning shell, the products of nucleosynthesis are predicted for a theoretical model of an exploding star. Using a previously constructed mass-density model, nucleosynthesis calculations are performed at eight points and yield, together with the zero point, eight mass zones. Explosive ignition of the $C^{12} + C^{12}$ reaction results in the formation of a detonation wave. Following the passage of this wave, a complete nuclear statistical equilibrium is established. During the subsequent expansion, the nuclear abundances progress through a sequence of equilibrium configurations until, at lower temperatures, the nuclear reactions are terminated. The parameters for the zones considered for nucleosynthesis are given in ATW's Table 1. This table gives the state of the plasma at the end of nucleosynthesis, which, according to ATW's Figure 2, occurs between 0.5 and 0.6 sec after the start of the detonation.

A parameter η is defined as a measure of the neutron excess over protons per nucleon present. During nucleosynthesis, an increase occurs in neutron excess $\Delta\eta$. Two values are considered which are referred to as the "low-η" and "high-η" cases. Since the low-η case is preferable, the following computations are carried out for this case only.

The agreement between the abundances predicted by the model and the iron group abundances observed in the solar system, if the meteoritic value for Fe is taken, is good. Many isotopic, as well as elemental, ratios are well reproduced. The C^{12} detonation model, however, does not produce any significant mass in the form of nuclei from Ne to Ca. If the iron group nuclei observed in nature are produced in C^{12} detonation supernovae, then the remaining nuclei must be generated in a different type of source.

For each mass zone, the results of the calculations of nucleosynthesis during the explosion are given in ATW's Table 3.

Since X-ray absorption depends only on the elemental composition of the zones, the isotopic abundances in ATW's Table 3 were combined to obtain zonal elemental abundance tables. To these metallic abundances are added the cosmic abundances of the light elements as given in Bell and Kingston's [2] Table 1, using these values for all zones. The total photon interaction cross sections of the elements were taken from the compilation of McMaster et al. [3]. The sum of the products of the elemental cross sections with the respective abundances gives the total photon interaction cross section for each zone.

The parameters for the exploding plasma in Table 1 were computed from the relevant parameters for nucleosynthesis in ATW's Tables 1 and 3. r is the radius of the concentric spheres, m is the mean atomic weight in each zone, N is the total number of particles in each zone, and n is the particle density in each zone. r is obtained from mass and density in each zone. N is obtained as the quotient of the mass and the product of m and the atomic mass unit in each zone. n is obtained as the quotient of N and the volume of the zone.

The product of n with the interaction cross sections gives the attenuation coefficient for each zone. The results are contained in Table 2.

III. THE ATTENUATION IN THE FILAMENTS OF THE CRAB NEBULA

To compute the attenuation of X rays in the filaments of the Crab Nebula, the narrow beam attenuation approximation has been adopted:

$$I(x) = I(0)\, e^{-\mu x}$$

$$\kappa = \frac{\mu}{\rho}$$

where μ (cm^{-1}) denotes the attenuation coefficient and κ ($cm^2\, g^{-1}$) is the mass attenuation coefficient. The calculations were carried out for a plane-parallel geometry with a normally incident beam of radiation for $T = 10\,000°$ K, $n_H = 1000\ cm^{-3}$, and for two plasma compositions. One is Woltjer's abundance of elements in the Crab Nebula [4] and the other is Davidson and Tucker's Model 2 [5]. The values are given in Table 3.

The attenuation coefficients of the elements were obtained from tables published by Henke and collaborators [6] and by McMaster and collaborators [3]. The mass attenuation coefficients for He, C, N, O, and Ne, 2 to 12 Å, and S, 1 to 12 Å, were taken from Henke and collaborators; the coefficients for He, C, N, O, 1 Å, and H, 1 to 12 Å, were taken from McMaster and collaborators.

The attenuation coefficients of the filaments were computed from the formula:

$$\mu = \frac{1}{N_0} \sum_z \kappa_z A_z n_z$$

where A denotes the atomic weight, N_0 Avogadro's number, and n the number of atoms per cubic centimeter, given in Table 4. The results are also contained in Table 4.

According to Davidson and Tucker [5], a typical filament has an apparent thickness of 2 sec of arc, yielding at 2020 pc:

$$x = 6.04 \cdot 10^{16}\ \text{cm} \quad .$$

It is seen that for all practical purposes the attenuation in the filaments can be neglected.

IV. THE ATTENUATION IN THE INTERSTELLAR MEDIUM

Gorenstein, Kellogg, and Gursky [7] have represented the optical thickness τ for three supernova remnants by the empirical expression:

$$\tau = \left(\frac{Ea}{E}\right)^{8/3}$$

where Ea and E are measured in keV. Ea varies for each remnant. The following values are given:

Crab Nebula:	$Ea \leq 0.9$ keV	$1 < E < 12$ keV
Cas A:	$Ea = 1.35$ keV	$1 < E < 10$ keV
Tycho:	$Ea \leq 1.6$ keV	$1 < E < 10$ keV

The results of Gorenstein et al., which will be called the "observed values," were compared with the corresponding results of the conventional method to represent τ:

$$\tau = \mu x,$$

where μ denotes the attenuation coefficient of the interstellar medium and x the distance of the source from the observer. The attenuation coefficients of the interstellar medium as computed by Schocken [8] were used. The calculations were carried out between 1 and 15 keV (12.398 to 0.827 Å). The observed values were at first compared with the corresponding optical thicknesses resulting from hydrogen alone as attenuating gas. It is then seen that the observed optical thickness becomes smaller than the optical thickness in hydrogen (1 atom cm^{-3}) for the Crab Nebula at 8 keV, for Cas A at 10 keV, and for Tycho at 9 keV. Since the attenuation of the interstellar medium cannot become smaller than that of hydrogen, it is concluded that the experimental method used by Gorenstein et al. furnishes the photoelectric absorption but not the scattering and, therefore, not the full attenuation. The method is, therefore, limited to the range between 1 and 7 keV.

If the observed values do not contain the contribution due to scattering, no further quantitative conclusions can be drawn; but it may be significant that in the indicated range the observed values of the Crab Nebula are very closely approximated by Schocken's [8] cosmic mixture No. 1:

H 1 atom cm^{-3}

He 0.16 atom cm^{-3},

and that the observed values of Cas A and of Tycho are very closely approximated by the values of the cosmic mixture No. 2:

H 1 atom cm^{-3}

He 0.16 atom cm^{-3}

C $3.98 \cdot 10^{-4}$ atom cm^{-3}

N $1.12 \cdot 10^{-4}$ atom cm^{-3}

O $8.91 \cdot 10^{-4}$ atom cm^{-3}

TABLE 1. PARAMETERS FOR THE DETERMINATION OF THE X-RAY ATTENUATION IN THE C^{12} DETONATION SUPERNOVA MODEL

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
r (cm)	$6.7611 \cdot 10^{7}$	$1.3916 \cdot 10^{8}$	$1.8822 \cdot 10^{8}$	$2.3038 \cdot 10^{8}$	$2.4774 \cdot 10^{8}$	$2.7731 \cdot 10^{8}$	$2.9987 \cdot 10^{8}$	$3.2632 \cdot 10^{8}$
m	56.469	56.572	56.904	57.580	57.860	57.392	56.326	53.331
$\dot{N}$	$1.5188 \cdot 10^{54}$	$6.0640 \cdot 10^{54}$	$6.0412 \cdot 10^{54}$	$5.9911 \cdot 10^{54}$	$2.7534 \cdot 10^{54}$	$3.6315 \cdot 10^{54}$	$1.9139 \cdot 10^{54}$	$1.3476 \cdot 10^{54}$
n (cm^{-3})	$1.1731 \cdot 10^{30}$	$6.0677 \cdot 10^{29}$	$3.6300 \cdot 10^{29}$	$2.5725 \cdot 10^{29}$	$2.2066 \cdot 10^{29}$	$1.4166 \cdot 10^{29}$	$8.1043 \cdot 10^{28}$	$4.1329 \cdot 10^{28}$

TABLE 2. μ (cm^{-1}), ATTENUATION COEFFICIENTS FOR X RAYS IN THE C^{12} DETONATION SUPERNOVA MODEL

keV	λ (Å)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
1000	0.012	$6.7178 \cdot 10^{6}$	$3.4701 \cdot 10^{6}$	$2.0859 \cdot 10^{6}$	$1.4951 \cdot 10^{6}$	$1.2884 \cdot 10^{6}$	$8.2030 \cdot 10^{5}$	$4.6065 \cdot 10^{5}$	$2.2260 \cdot 10^{5}$
500	0.025	$9.4225 \cdot 10^{6}$	$4.8730 \cdot 10^{6}$	$2.9253 \cdot 10^{6}$	$2.0970 \cdot 10^{6}$	$1.8074 \cdot 10^{6}$	$1.1509 \cdot 10^{6}$	$6.4633 \cdot 10^{5}$	$3.1231 \cdot 10^{5}$
100	0.124	$3.9795 \cdot 10^{7}$	$2.0498 \cdot 10^{7}$	$1.2316 \cdot 10^{7}$	$8.8463 \cdot 10^{6}$	$7.6611 \cdot 10^{6}$	$4.8993 \cdot 10^{6}$	$2.7534 \cdot 10^{6}$	$1.3287 \cdot 10^{6}$
50	0.248	$2.0562 \cdot 10^{8}$	$1.0577 \cdot 10^{8}$	$6.3540 \cdot 10^{7}$	$4.5693 \cdot 10^{7}$	$3.9686 \cdot 10^{7}$	$2.5436 \cdot 10^{7}$	$1.4301 \cdot 10^{7}$	$6.8962 \cdot 10^{6}$
10	1.240	$1.8500 \cdot 10^{10}$	$9.5263 \cdot 10^{9}$	$5.7238 \cdot 10^{9}$	$4.1152 \cdot 10^{9}$	$3.5705 \cdot 10^{9}$	$2.2864 \cdot 10^{9}$	$1.2849 \cdot 10^{9}$	$6.1944 \cdot 10^{8}$
5	2.480	$1.5180 \cdot 10^{10}$	$7.8079 \cdot 10^{9}$	$4.6896 \cdot 10^{9}$	$3.3695 \cdot 10^{9}$	$2.9266 \cdot 10^{9}$	$1.8773 \cdot 10^{9}$	$1.0562 \cdot 10^{9}$	$5.1000 \cdot 10^{8}$
1	12.398	$9.9688 \cdot 10^{11}$	$5.1392 \cdot 10^{11}$	$3.0889 \cdot 10^{11}$	$2.2192 \cdot 10^{11}$	$1.9204 \cdot 10^{11}$	$1.2265 \cdot 10^{11}$	$6.8867 \cdot 10^{10}$	$3.3190 \cdot 10^{10}$

TABLE 3. RELATIVE ABUNDANCES BY NUMBER IN TWO MODELS FOR THE FILAMENTS OF THE CRAB NEBULA

Element	Model No. 1 Woltjer	Model No. 2 Davidson and Tucker
H	1000	1000
He	449.438	1000
C	-	0.2
N	0.607	0.2
O	1.124	0.6
Ne	0.618	0.2
S	0.348	-

TABLE 4. ATTENUATION COEFFICIENTS OF THE FILAMENTS FOR TWO MODELS

	cm^{-1}	
	10^{-20}	
Å	Woltjer	Davidson and Tucker
1	0.2150	0.2284
2	0.7503	0.4073
3	2.0501	0.8255
4	4.5502	1.9479
5	8.4254	3.7170
6	7.5043	6.2500
7	11.60	9.8912
8	16.93	14.76
9	23.51	20.95
10	31.69	28.80
11	41.73	38.69
12	52.94	50.13

REFERENCES

1. Arnett, W. D.; Truran, J. W.; and Woosley, S. E.: Astrophys. J., no. 165, 1971, p. 87.

2. Bell, K. L. and Kingston, A. E.: Mon. Not. R. Astr. Soc., no. 136, 1967, p. 241.

3. McMaster, W. H.; Del Grande, N. Kerr; Mallett, J. H.; and Hubbell, J. H.: Compilation of X-Ray Cross Sections. UCRL-50174, Sec. II, Rev. 1, 1969.

4. Woltjer, L.: Bull. Astron. Inst. Netherlands, no. 14, 1958, p. 39.

5. Davidson, K. and Tucker, W.: Astrophys. J., no. 161, 1970, p. 437.

6. Henke, B. L.; Elgin, R. L.; Lent, R. E.; and Ledingham, R. B.: X-Ray Absorption in the 2 to 200Å Region. Norelco Reporter 14, 1967, pp. 112-134.

7. Gorenstein, P.; Kellogg, E. M.; and Gursky, H.: Astrophys. J., no. 160, 1970, p. 199.

8. Schocken, K.: J. Appl. Phys., no. 43, 1972, p. 3575.

APPROVAL

THE ATTENUATION OF X RAYS EMITTED BY SUPERNOVAE

By Klaus Schocken

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

William C. Snoddy

WILLIAM C. SNODDY
Chief, Space Thermophysics Division

W. Haeussermann

W. HAEUSSERMANN
Acting Director, Space Sciences Laboratory

DISTRIBUTION

INTERNAL

DEP-T

S&E-DIR
Dr. Hermann Weidner

PD-MP-DIR
Mr. Herman Gierow

S&E-AERO-T
Dr. Helmut Krause

S&E-SSL-DIR
Dr. W. Haeussermann
Mr. Ray Hembree

S&E-SSL-C
Reserve (5)

S&E-SSL-N
Dr. Rudolf Decher

S&E-SSL-P
Dr. Robert Naumann

S&E-SSL-S
Dr. Werner Sieber

S&E-SSL-T
Mr. William Snoddy
Dr. Klaus Schocken (10)

S&E-SSL-TE
Mr. Ed Miller
Mr. Harry Atkins
Mr. Walter Fountain
Mr. James Fountain
Mr. Stanley Fields
Mr. John Reynolds
Mr. Charles Baugher
Mr. Ed Reichmann
Mr. Robert Wilson
Dr. Thomas Wdowiak

S&E-SSL-TR
Mr. Gary Arnett
Mr. Tommy Bannister
Dr. Roger Kroes
Mr. Roger Linton
Mr. Donald Wilkes
Mr. James Zwiener
Mrs. Barbara Facemire

S&E-SSL-TT
Mr. Billy Jones
Mr. Daniel Gates
Mr. Paul Craven
Mr. Jimmy Watkins
Dr. Mona J. Hagyard
Mr. Ted Calvert
Dr. Gilmer Gary

S&E-SSL-X
Mr. Hoyt Weathers

A&PS-PAT
Mr. L. D. Wofford, Jr.

A&PS-MS-IP (2)
A&PS-MS-IL (8)
A&PS-MS-H
A&PS-TU (6)

EXTERNAL

NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771
Attn: Dr. A. Boggess, Code 672
Dr. K. Hallam, Code 673
Dr. T. Stecher, Code 672
Dr. E. Boldt, Code 661

Johnson Space Center
Houston, Texas 77058
Attn: Dr. Yoji Kondo, TN23

Scientific and Technical Information
Facility (25)
P.O. Box 33
College Park, Maryland 20740
Attn: NASA Representative (S-AK/RKT)

Dr. Edward J. Devinney
Department of Astronomy
University of South Florida
Tampa, Florida 33620

Dr. Laurence E. Peterson
Department of Physics
Space Physics Group
University of California
La Jolla, California 92037

Dr. J. H. Hubbell
Center for Radiation Research
National Bureau of Standards
Washington, D. C. 20234

Dr. J. E. Felten
Institute of Theoretical Astronomy
Madingley Road
Cambridge, England CB30F2

Dr. Donald G. Burkhard
Physics Department
University of Georgia
Athens, Georgia 30601

Hayes International Corporation
Huntsville, Alabama
Attn: Mr. Weissinger