ASTROPHYSICS AND SPACE SCIENCE LIBRARY

INVESTIGATING THE UNIVERSE

Edited by F. D. Kahn

VOLUME 91

D. REIDEL PUBLISHING COMPANY

DORDRECHT, HOLLAND / BOSTON, U.S.A. / LONDON, ENGLAND

INVESTIGATING THE UNIVERSE

Papers presented to Zdeněk Kopal
on the occasion of his retirement, September 1981

WITH A FOREWORD BY M.K.V. BAPPU,
PRESIDENT OF THE INTERNATIONAL ASTRONOMICAL UNION

Edited by

F. D. KAHN
Department of Astronomy, The University of Manchester, England

D. REIDEL PUBLISHING COMPANY
DORDRECHT : HOLLAND / BOSTON : U.S.A.
LONDON : ENGLAND

Library of Congress Cataloging in Publication Data

Main entry under title:

Investigating the universe.

(Astrophysics and space science library ; v. 91)
Includes index.
1. Astrophysics-Addresses, essays, lectures. 2. Astronomy-Addresses, essays, lectures. 3. Kopal, Zdeněk, 1914- I. Kopal, Zdeněk, 1914- . II. Kahn, F. D. (Franz Daniel). III. Series.

QB461.5.I56 523.01 81-12013
ISBN 90-277-1325-1 AACR2

Published by D. Reidel Publishing Company,
P.O. Box 17, 3300 AA Dordrecht, Holland.

Sold and distributed in the U.S.A. and Canada
by Kluwer Boston Inc.,
190 Old Derby Street, Hingham, MA 02043, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers Group,
P.O. Box 322, 3300 AH Dordrecht, Holland.

D. Reidel Publishing Company is a member of the Kluwer Group.

Printed in The Netherlands

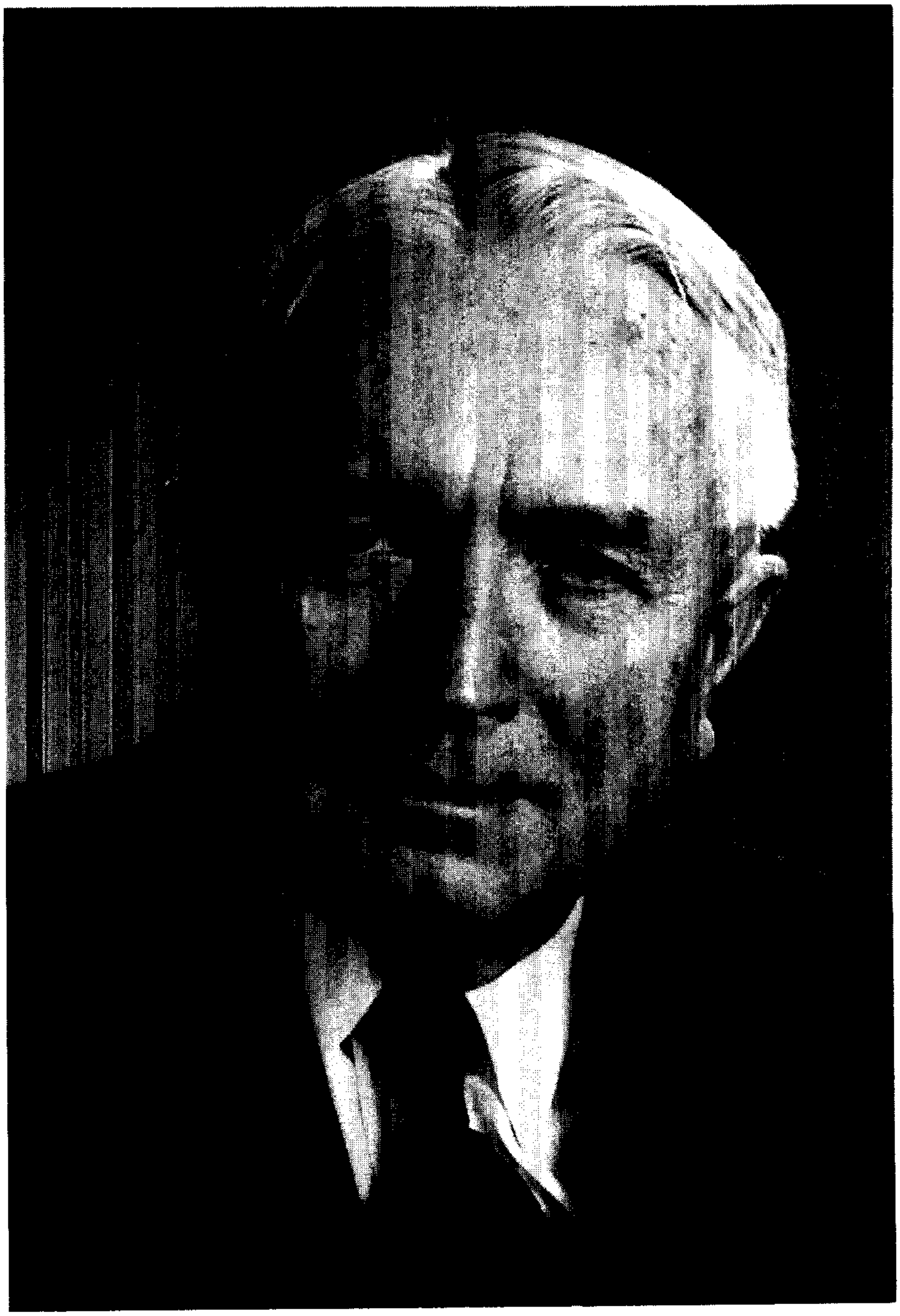
ACKNOWLEDGEMENTS

It is evident that a volume like this cannot be produced without much painstaking work by the publishers and the typists involved. The Editor is especially grateful to the staff of Reidel's for their assistance and courtecy, and to Barbara Barlow, Ellen Carling and Joanne Suthers for their constant willingness to help.

CONTRIBUTORS

in alphabetical order

M. K. V. Bappu	Indian Institute of Astrophysics, Bangalore
A. H. Batten	Dominion Astrophysical Observatory, Victoria B.C.
E. Budding	Department of Astronomy, University of Manchester
J. Cantó	Institute of Astronomy, National University of Mexico
M. A. Dopita	Mount Stromlo and Siding Spring Observatories, Canberra
J. E. Dyson	Department of Astronomy, University of Manchester
C. Goudas	Department of Mathematics, University of Patras
J. Hazlehurst	Hamburg Observatory
R. A. James	Department of Astronomy, University of Manchester
F. D. Kahn	Department of Astronomy, University of Manchester
M. Kitamura	Tokyo Astronomical Observatory
J. Meaburn	Department of Astronomy, University of Manchester
D. A. Mendis	University of California at San Diego
M. G. Smith	Royal Observatory, Edinburgh
P. Stewart	Department of Mathematics, University of Manchester



PROFESSOR ZDENĚK KOPAL

FOREWORD

Professor Zdeněk Kopal is sixty-seven this year even though his scientific activity, enthusiasm and springy step hardly betray the advancement in years. He came to Manchester as Professor of Astronomy thirty years ago after a very fruitful association of fourteen years with the Harvard Observatory. Much impressed with the young man, Harlow Shapley, who with characteristic insight had recognised in Kopal the qualities that have since made him an outstanding leader in eclipsing binary research, had invited him over as a Research Associate. In the subsequent decade Kopal set about the task of introducing analytical rigour in the solution of orbital elements that hitherto had depended exclusively on the semigraphical procedures introduced by Russell and exploited fully by Shapley. These first efforts stimulated publication of the first of his many books on eclipsing variables; the *Introduction to the Study of Eclipsing Variables* summarized these iterative methods and remains a classic in this field. Soon after the appearance of this volume in print, Kopal gave a course on this subject for the graduate students at Harvard. I was one of those who had the opportunity to attend it and learn much on the need of care and precision in the practice of photoelectric photometry and the importance of exploiting such data to the fullest extent with methods of increasing resolving power. The RCA 1P21 photomultiplier tube had just begun to revolutionize photoelectric photometry and make it accessible to the several small instruments scattered all over the world. It was a tide in astronomical practice that could be fully swung over to maximize the availability of the basic astrophysical parameters, and much of the happy position we are in today in this regard stems from the lively role Kopal has played as a member and subsequently as President of IAU Commission 42.

Since then at Manchester, Kopal has had a very flourishing school whose contributions have continuously taken advantage of the increasing new facilities for quick and elaborate computation. The transition from the time to the frequency domain was timely from the standpoint of available means of automatic computation. The large machines can solve for the elements of a system in a fantastically short interval. Kopal's recent efforts have been to achieve similar goals with simpler computation facilities.

Many years ago, that pioneer of eclipsing binary analysis, Henry Norris Russell, delighted in having his undergraduate class solve the elements of a system with the aid of a slide rule. We have come a full circle today from this simple graphical procedure to something that can be done in the same time with great elegance and analytical rigour. This

F. D. Kahn (ed.), Investigating the Universe, ix–x.

transformation is undoubtedly the result of the Kopal era in the study of eclipsing binaries.

This Festschrift Volume is an expression of admiration, appreciation and gratitude from the many who have been Professor Kopal's students and collaborators. May the years ahead hold for him much happiness and continued creative scientific activity.

M. K. V. Bappu,
President,
International Astronomical Union

TABLE OF CONTENTS

Section V: Modelling of Galaxies

DYNAMICS OF THE GALACTIC FOUNTAIN

F. D. Kahn
Department of Astronomy, University of Manchester.

The visitor to Zdenek's office will have noticed a cupboard fixed to the outside wall. It is filled with theses written by former students of the Department. Even though the building is immensely strong and the cupboard well made I have often worried that the weight of knowledge stored inside it would one day bring it down.

Much the same problem faced us when planning this collection of papers. Had we invited contributions from everyone who qualified then everyone would have accepted. The resulting volume would have been much too large even for Reidel's, our generous publisher. What is worse, Zdenek would have been unable to lift it up and read it. We therefore had to make a somewhat arbitrary selection of authors, and now apologise to those whom we could not invite. But we are sure that they join us in wishing Zdenek well. Of course we also thank all the contributors who have written such interesting and topical papers.

In presenting this volume to you, Zdenek, we ask you to regard it as a token of the great success achieved by the Department that you founded in the autumn of 1951. May you have a long, happy and active retirement.

Under ordinary circumstances I should have broken off here and got on with the astrónomy. But circumstances are far from ordinary. In the spring of 1951 I married Carla, having got to know her a few months earlier. There followed a union uniquely blessed by love and happiness. We had many children, and even a grandchild, and through our different activities, notably the astronomical ones, we acquired a worldwide circle of very good friends. All seemed set to go on in this way when one morning in January this year Carla suffered a severe stroke, and then died on the evening of the next day.

It is a commonplace that life can be cruel. But fortunately fate only very rarely administers so devastating a blow. This paper deals with the first scientific work that I have attempted since Carla's death. I dedicate it to her memory, may she rest in peace.

F. D. Kahn (ed.), Investigating the Universe, 1–28.

I. THE HOT INTER-CLOUD MEDIUM IN THE GALAXY

In this paper I shall discuss the properties of the hot inter-cloud medium (ICM); to do so something needs to be said about the input of energy, mainly from supernova explosions, about radiative processes which cause substantial cooling, and about the dynamical consequences of having gas in the Galaxy which is so hot that its thermal velocity far exceeds the escape velocity from the galactic disk, but not from the Galaxy as a whole. There is an intricate inter-relation between these various aspects, so that I shall cautiously approach the problem by a series of successive approximations.

The most striking result of having so much gas that cannot be confined is that there develops a fountain which carries some of the interstellar matter far from the galactic plane. This effect has been extensively discussed, in the last two years, in a series of papers by Bregman. His model is two-dimensional and allows for the fountain to spray both upwards from the plane and outward, away from the axis. But eventually the gas loses its thermal energy, and therefore, to maintain pressure, it condenses into cool clouds which fall back inwards and towards the galactic plane. Bregman's model shows a very encouraging correspondence between theory and observation, and may well settle some difficult astrophysical problems, such as the origin of the absorption lines seen in distant quasars.

But in this paper I shall take a different point of view, and explore the consequences. If the gas is to accelerate in a radial direction, as well as perpendicular to the plane, then it must have a cooling time that is sufficiently long. The most likely origin of the hot gas is in supernova remnants. Most of a supernova remnant will have lost its thermal energy by the time that its internal pressure has dropped to interstellar values. At that stage the remaining hot gas will itself have a cooling time whose length is of the order of ten times the age of the remnant. During this time the gas can rise only a relatively short distance from the plane. If there exist pressure changes in the radial direction on a length scale comparable with the distance to the galactic centre, then the pressure gradient will still be overwhelmingly in the upward direction. A one-dimensional description will therefore be quite adequate. But of course it does not at first sight give anything like as good an account of the observed properties of the halo gas, notably of the high velocity clouds. This point will be taken up again later.

The first requirement for a model is a suitable description of the gravitational field in and above the galactic disk. As is well known the overall field of the Galaxy is such that the speed V of a star in a circular orbit is independent of the orbital radius, and equals some 250 km s^{-1}. The mass distribution that gives rise to the corresponding gravitational field is widely believed to be due to a spherical halo of Population II objects. Thus the mass M(r) within a radial distance r is given by

$$M(r) = V^2 r/G \equiv \mu r \tag{1}$$

where $\mu = 9.4 \times 10^{21}$ gm cm^{-1}.

When considering the equilibrium of the ICM in our model we are concerned mainly with the component g_z of the gravitational field perpendicular to the galactic plane. The contribution made by the spherical halo population to this component is denoted by $g_z^{(h)}$; another contribution $g_z^{(d)}$ comes from the mass in the disk of the Galaxy, or Population I, and I shall deal with that shortly.

At a height z above the galactic plane the gravitational potential is

$$\mathcal{V}(z, R_*) = -\tfrac{1}{2} G\mu \log(1 + z^2/R_*^2) \tag{2}$$

with respect to the point, at radial distance R_*, in the plane directly underneath. Provided z is small in comparison with the galactocentric distance R_*,

$$g_z^{(h)} = \frac{G\mu z}{R_*^2 + z^2} \doteq \frac{G\mu z}{R_*^2} = \frac{V^2 z}{R_*^2} \tag{3}$$

At the Sun's distance from the centre R_* is some 10 kpc and so

$$g_z^{(h)} = 6.9 \times 10^{-31} z. \tag{4}$$

To estimate the contribution made to g_z by matter in the galactic disk, consider the typical dispersion $\bar{\sigma}$ of z-components of velocity of extreme Population I objects; typically $\bar{\sigma}$ is 10 km s^{-1}. These objects fill a layer that rises to a height D $\sim$ 100pc above the plane. Given a uniform distribution of Population I mass near the plane it follows that, for z sufficiently small,

$$g_z^{(d)} = \frac{\bar{\sigma}^2}{D^2} z \equiv \gamma z, \tag{5}$$

and, with the values adopted here,

$$\gamma = 1.1 \times 10^{-29} \quad s^{-2}. \tag{6}$$

Close to the galactic plane the disk population contributes overwhelmingly to g_z. The necessary mass density is

$$\rho = \gamma/4\pi G = 1.3 \times 10^{-23} \text{gm cm}^{-3} \tag{7}$$

Models of the Galaxy in common use ascribe some 20 per cent of the mass to the disk population. In the spirit of this series of rough estimates it follows that the total mass of the disk population out to galactocentric distance 10 kpc is thus about 5.6 x 10^{43} gm. Assume now that the disk material is also distributed in such a way that the mass out to radius r is proportional to r. Then the local value of the half surface density at the Sun's distance from the centre is

$$\Sigma_d(R_*) = 5.0 \times 10^{-3} \text{ gm cm}^{-2}. \tag{8}$$

A comparison with relation (7) indicates that the half-thickness of this mass distribution is

$$Z = \Sigma_d(R_*)/\rho_d = 3.8 \times 10^{20} \text{ cm} = 127 \text{ pc}. \tag{9}$$

The gravitational potential at height z, with respect to a point in the galactic plane directly below, is therefore

$$\vartheta \doteqdot -\tfrac{1}{2}\gamma z^2 \tag{10}$$

if z < Z, and

$$\vartheta = -\left\{\gamma Z(z-Z) + \tfrac{1}{2}\gamma Z^2 + (V^2/2R_*^2)z^2\right\}, \tag{11}$$

if z > Z, in reasonable approximation.

The hot ICM has a temperature T of around 10^6K. It is fully ionized so that $\bar{m}$ the mean particle mass, is 10^{-24}gm, and the isothermal sound speed is

$$c_s = \sqrt{kT/\bar{m}} \doteqdot 120 \text{ km s}^{-1} \tag{12}$$

If the gas were to remain uncooled it would be expected to rise to a height z such that

$$kT/\bar{m} = c_s^2 \sim \vartheta(z) \tag{13}$$

The time needed to establish hydrostatic equilibrium would be of the order of

$$t_{eq} = z/c_s \tag{14}$$

But the hot gas will radiate following the excitation of various ion species by electron impact. A useful approximation is that the rate of loss of energy by radiation, per ion, is

$$L = \lambda n T^{-1/2} \tag{15}$$

at temperature T, where n is the density of atoms plus ions, and

$$\lambda \doteq 1.33 \times 10^{-19} \tag{16}$$

in CGS units. The formula is applicable in the range of temperatures between 2×10^5K and 10^8K.

The cooling law can be most usefully formulated in terms of the adiabatic parameter

$$K \equiv P/\rho^{5/3}, \tag{17}$$

which is related to the specific entropy S by

$$S = (3k/2m) \log K . \tag{18}$$

The density is given by

$$\rho = n m_a , \tag{19}$$

where m_a is the average mass per atom, and then the rate of loss of energy per unit mass can be expressed by

$$T \frac{dS}{dt} = -\frac{L}{m_a} = -\frac{\lambda n}{m_a} T^{-1/2} = -\frac{\lambda \rho}{m_a^2} T^{-1/2} . \tag{20}$$

Here d/dt denotes rate of change following the motion of the fluid. Then using relation (18), as well as the equation of state

$$P = (k/\bar{m}) \rho T, \tag{21}$$

it can be shown that

$$\frac{d}{dt} K^{3/2} = -q , \tag{22}$$

where

$$q \equiv \frac{\lambda k^{1/2}}{m_a^2 \bar{m}^{1/2}} = 4 \times 10^{32} \, (cm^6 gm^{-1} s^{-4}).$$

Relation (22) implicitly assumes that there are no other significant sources of pressure support, such as a magnetic field.

The cooling time for an element of the hot gas is thus

$$t_c = \kappa^{3/2}/q = P^{3/2}/q\rho^{5/2}. \tag{23}$$

So there is no possibility for the hot ICM to establish hydrostatic equilibrium if

$$t_{eq} \equiv \frac{\mathfrak{z}}{c_s} > t_c = \frac{P^{3/2}}{q\rho^{3/2}} = \frac{c_s^3}{q\rho} \tag{24}$$

or

$$c_s^4 < q\rho\mathfrak{z}, \tag{25}$$

where z is given by equation (13) and ρ is the density of the hot medium in the galactic disk. It may be preferable to express this inequality in terms of the interstellar pressure P so as to read

$$c_s^6 < qP\mathfrak{z}. \tag{26}$$

With typical values $P = 10^{-12}$ dyne cm^{-2}, $c_s = 10^7$ cm s^{-1}, this means that cooling occurs too fast for hydrostatic equilibrium to be possible in any halo whose height z is larger than or of the order of

$$c_s^6/qP = 4 \times 10^{21} cm = 1.3 \text{ kpc}. \tag{27}$$

On the other hand equations (12) and (13) lead to an estimated scale height of some 1.1×10^{22} cm = 3.7 kpc for a static halo, if the sound speed is $c_s \sim 100$ km s^{-1}. Thus the inter-cloud medium is too hot to be confined by the gravitational field to the layer occupied by Population I. The gas rises away from the plane towards an equilibrium structure with considerably greater thickness, but loses its thermal energy long before the new configuration is reached. The inter-cloud medium can never attain equilibrium in a static structure. The correct description of the halo must be dynamic.

II. INPUT OF HEAT INTO THE INTER-CLOUD MEDIUM

Supernova explosions are the most likely source of energy for the inter-cloud medium. The growth of a supernova remnant is well described by the famous Sedov solution. In this model it is assumed that the energy input occurs in a small volume and affects initially only a small mass. But as the disturbance spreads it entrains progressively more interstellar matter. A basic requirement of the Sedov solution is that the interstellar gas be uniformly distributed before the shock wave overtakes it. Here is a great difficulty. The very existence of the inter-cloud medium shows that large regions of space contain gas whose density is much below the interstellar average. In fact the bulk of the interstellar mass resides in cool clouds that occupy only a small fraction of the available volume. It is certainly not possible to argue that the shock from an expanding supernova remnant will by-pass these dense clouds and heat only the inter-cloud medium. If that were so the ICM would be expelled from the galactic disk in a very short time, and would immediately need to be replaced. Therefore the cool clouds must also be heated, since they are the only possible source of mass for the galactic fountain.

An immediate consequence is that there must be a means whereby the thermal energy left behind by a shock wave is conducted or convected into the cool clouds, and then causes them to heat up, expand and become part of the ICM. Various schemes have been proposed for this transport of heat. There are also modified solutions of the Sedov type which mimic the way in which matter in the clouds partially evaporates and joins the expanding bubble of hot gas behind the shock. But at present there is only limited understanding of the conduction process: the interstellar magnetic field will clearly be important since thermal conduction across the lines of force is always very small. Even the rate at which conduction occurs along the lines of force may be severely inhibited by various plasma instabilities which can arise if the field strength is low enough. So, knowing full well that the model is inadequate, I shall nevertheless assume that the unshocked interstellar gas is uniform, at density ρ_o, and that it is cool.

Such a procedure yields the most conservative estimate for the rate of input of energy into the ICM. The existence of regions of high density in the interstellar gas must mean that some parts of the medium are protected from the input of heat. The available energy is therefore shared among only a fraction of the available gas, with consequences that are the same as if the medium had been uniform, but with a density lower than $\bar{\rho}_o$, the actual smoothed-out value. The ICM contains that part of the gas from various supernova remnants which takes the longest time to cool, that is the gas which attains the largest value of $K (\equiv P/\rho^{5/3})$ behind the blast wave. The mass of gas which can be raised above any given K increases as ρ_o is decreased. By overestimating the effective ρ_o one underestimates the contribution of a supernova explosion in heating the inter-cloud medium.

The Sedov solution applies only during the so-called Phase II of a supernova remnant, which occurs when enough time has elapsed that the mass entrained much exceeds the mass ejected by the original explosion, but not so much time has passed that cooling has become important. At time t the shock radius is then given by

$$r = a t^{2/5} \tag{28}$$

where

$$a^5 \doteq 2E/\rho_o \quad , \tag{29}$$

and E is the energy released by the explosion. The shock speed

$$\dot{r} = \tfrac{2}{5} a t^{-3/5} \qquad (30)$$

is so much larger than the sound speed in the undisturbed medium ahead that the shock can be taken to be strong. The post-shock pressure and density are, respectively,

$$P_s = \tfrac{3}{4} \rho_0 \dot{r}^2 \quad \text{and} \quad \rho_s = 4\rho_0 \ , \qquad (31)$$

and the adiabatic parameter just behind the shock is

$$K_s = \frac{P_s}{\rho_s^{5/3}} = \frac{3a^2}{25 \times 2^{10/3} \rho_0^{2/3}} t^{-6/5} . \qquad (32)$$

In the absence of thermal conduction an element of gas will retain the value of K it attained behind the shock until radiative losses become important for it. At time t a mass

$$M_s = (4\pi/3) \rho_0 a^3 t^{-6/5} \qquad (33)$$

has passed through the shock. In the subsequent evolution of the gas in the remnant, the mass M within which the adiabatic parameter exceeds some given value K_* satisfies the relation

$$K_* M = \frac{\pi}{25 \times 2^{4/3}} \rho_0^{1/3} a^5 = \frac{\pi}{25 \times 2^{1/3}} \frac{E}{\rho_0^{2/3}} \doteq \frac{0.1 E}{\rho_0^{2/3}} . \qquad (34)$$

Eventually radiative cooling sets in, beginning in the outer parts of the remnant. At that time the Sedov solution becomes inapplicable, but relation (34) is still valid for any fluid element that passed through the shock during Phase II, and has not yet started to lose energy by radiation at a significant rate.

When an uncooled mass M has come to equilibrium under external pressure P, a range dK of the adiabatic parameter corresponds to a mass

$$dM = \frac{0.1 E \, dK}{\rho_0^{2/3} K^2} , \qquad (35)$$

and occupies an element of volume

$$dV = \frac{dM}{\rho} = \frac{0.1 E \, dK}{\rho_0^{2/3} P^{3/5} K^{7/5}} . \qquad (36)$$

The volume occupied by mass $M = 0.1 E/\rho_0^{2/3} K_*$ is

$$V = \tfrac{5}{2} \left(\frac{0.1 E}{\rho_0^{2/3}} \right) K_*^{-2/5} P^{-3/5} = \tfrac{5}{2} K_*^{3/5} M P^{-3/5} . \qquad (37)$$