SOCIETA' ITALIANA DI FISICA

RENDICONTI
DELLA
SCUOLA INTERNAZIONALE DI FISICA
«ENRICO FERMI»

LXV CORSO

Physics and Astrophysics of Neutron Stars and Black Holes

SOCIETÀ ITALIANA DI FISICA - BOLOGNA (ITALY)

ITALIAN PHYSICAL SOCIETY

PROCEEDINGS
OF THE
INTERNATIONAL SCHOOL OF PHYSICS « ENRICO FERMI »

COURSE LXV

edited by R. GIACCONI and R. RUFFINI
Directors of the Course

VARENNA ON LAKE COMO
VILLA MONASTERO
14th-26th JULY 1975

Physics and Astrophysics of Neutron Stars and Black Holes

1978

NORTH-HOLLAND PUBLISHING COMPANY, AMSTERDAM · NEW YORK · OXFORD

Library of Congress Cataloging in Publication Data

Varenna, Italy. Scuola internazionale di fisica.
Physics and astrophysics of neutron stars and black holes.
(Proceedings of the International School of Physics « Enrico Fermi » = Rendiconti della Scuola internazionale di fisica « Enrico Fermi »; course 65).
At head of title: Italian Physical Society.
Added t.p.: Fisica ed astrofisica delle stelle di neutroni e dei buchi neri.
Course held July 14-26, 1975.
Bibliography: p.
1. Neutron stars—Congresses. 2. Black holes (Astronomy)—Congresses. I. Giacconi Riccardo.

Library of Congress Cataloging in Publication Data

II. Ruffini, Remo. III. Società Italiana di Fisica. IV. Title. V. Title: Fisica ed astrofisica delle stelle di neutroni e dei buchi neri.
QB843.N4V37 523.8 78-12340
ISBN 0-7204-0720-3

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a cura di R. GIACCONI e R. RUFFINI
Direttori del Corso

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Introduction.

On the grounds of Fermi-Dirac statistics and of the Einstein theories of gravitation and relativity, it was shown in the 1930's that only three different equilibrium configurations should be expected to exist for a star at the end-point of its thermonuclear evolution: white dwarfs, neutron stars or black holes [1].

S. CHANDRASEKHAR [2], following considerations of R. H. FOWLER [3], was able to give a direct explanation of the physical reasons governing the equilibrium configurations of white dwarfs: at densities of $\sim 10^5$ g/cm^3 the star is mainly composed of fully ionized nuclei embedded in a degenerate gas of electrons. The density of matter comes mainly from the nuclei, the pressure keeping the star in equilibrium comes from the Fermi pressure of the degenerate electron gas.

G. GAMOW [4] suggested that the Fermi pressure of a degenerate nucleon gas could have an essential role in determining the equilibrium configurations of matter at still higher densities. GAMOW showed that for a large enough number of cold self-gravitating nucleons, processes of inverse beta-decay should occur. A configuration of equilibrium then exists, at approximately nuclear densities, in which the pressure and density of the star are mainly given by a degenerate gas of neutrons. R. OPPENHEIMER and his students R. SERBER [5] and G. VOLKOFF [6] determined in a detailed treatment the masses, radii and density distributions of these neutron stars.

In both the analysis of the equilibrium configurations of white dwarfs, and of neutron stars, a new feature appeared: the existence of a critical mass against gravitational collapse. That merely on the ground of the special-relativistic dependence of the energy of a particle on its momentum would follow that a star kept in equilibrium by Fermi pressure should have a critical mass against gravitational collapse, had been independently pointed out by LANDAU [7] and CHANDRASEKHAR [1]. The analysis by CHANDRASEKHAR [8] of the equilibrium configurations gave for the critical mass of white dwarfs $M_{\text{crit}} = 1.44\, M_\odot$, while the analysis of Oppenheimer and Volkoff gave for neutron stars $M_{\text{crit}} = 0.7\, M_\odot$.

R. OPPENHEIMER was the first to understand that the unavoidability of the existence of a critical mass in the configurations of equilibrium of a star at the endpoint of thermonuclear evolution would naturally lead to the existence of configurations of « continued gravitational collapse ». By this process a star approaches asymptotically its own gravitational radius (« black hole »). In a classic paper written with SNYDER, OPPENHEIMER [8] gave, in complete analytical details, the description of this asymptotic approach of a star to a black hole, within the framework of Einstein's theory of gravitation.

W. BAADE and F. ZWICKY [9] gave an astrophysical setting for neutron stars by outlining the possible connections between their formation and the occurrence of supernovae. It was not until the discovery in 1968 of pulsars by J. BELL, A. HEWISH *et al.* [10] and especially by the discovery of the pulsar PSR 0531 + 21 [11, 12] at the centre of the Crab Nebula, that the actual discovery of neutron stars in our galaxy was accomplished. Simultaneously the association of neutron stars to supernovae remnants was at once proved.

The discovery of pulsars brought a profound revival in the theoretical analysis of neutron stars. The structure, the composition, the equation of state of neutron stars were re-examined in light of improved knowledge of nuclear physics. The macroscopic parameters of neutron stars, mass, radius, moment of inertia, were reanalysed and the electrodynamics of their magnetosphere approached for the first time [12]. Special attention was given in establishing a numerical upper limit to the value of the critical mass of neutron stars independently from the many unknowns in the equation of state at supranuclear densities [13]. In parallel to these works an extensive theoretical analysis started in predicting observational properties of black holes. This work was greatly enhanced by the discovery of new solutions of the Einstein-Maxwell equations, of great astrophysical interest, describing black holes endowed with mass, rotation and magnetic-field structures [14].

The launch of the first orbiting X-ray telescope by R. GIACCONI and his group in 1971 opened a new trend in the study of the physics and astrophysics of neutron stars and black holes. The discovery of many binary X-ray sources from by the Uhuru satellite gave for the first time data on the masses of neutron stars, information on the processes occurring deep in their magnetospheres and finally the first candidate for the identification of a black hole in our galaxy [1].

The scope of this LXXV « Enrico Fermi » summer school has been to review the progress made in recent years in our understanding of neutron stars and black holes in light of the extensive experimental knowledge acquired from binary X-ray sources. Emphasis has been given to review *a*) the experimental results, *b*) the theoretical analysis of the structure of neutron stars and black holes and *c*) the phenomenological analysis of the astrophysical processes in binary X-ray sources.

It was a great honour for all of us to have as one of the lecturers in this school Prof. S. CHANDRASEKHAR, who gave in the opening lecture a vivid historical recollection of the basic steps which have led to a deeper understanding of the late stages of evolution of stars.

In reviewing experimental results it is difficult in a field such as high-energy observational astronomy to present reviews which are not immediately rendered obsolete by new or more refined observations. We were particularly fortunate in conducting this course to be able to present authoritative reviews of the developments of the recent past pertaining to the optical, radio, X-ray and gamma-ray studies of X-ray sources, pulsars, X-ray and gamma-ray bursters, as well as results from operational space observatories, such as ANS, Ariel and SAS-C.

The main conclusions from the UHURU surveys, presented by R. GIACCONI, were confirmed and extended by the findings of Ariel V, presented by K. POUNDS. The significance of the association of X-ray sources with globular clusters was particularly stressed by G. CLARK, who responded on the SAS-C and OSO VII results. H. TANANBAUM reported on the ANS studies of globular cluster sources. The continuation of these studies was soon to lead to the discovery of the first identified X-ray burst source by J. GRINDLAY and H. GURSKY [15]. The detailed findings on the optical properties of X-ray binaries were surveyed by J. BAHCALL and Y. AVNI. They reviewed critically the consequences of these observations with respect to mass determination of the collapsed stars in the binary systems. J. B. HUTCHINGS also emphasized recent results obtained in the optical range of wavelenghts. P. E. BOYNTON presented detailed observations pertaining to Her X-1, and emphasized the very tight constraints placed by these observations on any possible model. J. NELSON described the use of the phase dependence of the optical pulsations from Her X-1 to infer a value of the mass of a neutron star. R. M. HJELLMING reviewed the radio measurements of X-ray sources, and J. TAYLOR discussed extensive surveys of pulsars as well as the detailed measurements of the parameters of the binary pulsar [16]. I. B. STRONG summarized the results on gamma-ray burst sources. Soon after this school, the study of X-ray bursters, globular cluster sources and their relation to gamma-ray burst sources underwent a very rapid development which has been summarized in recent reviews presented by J. GRINDLAY, W. LAWIN and H. GURSKY [17]. Finally progress in the construction of gravitational-wave detectors has been reported by W. FAIRBANK.

In the theoretical field a general review of black-hole properties, relevant for astrophysical processes, has been given by R. RUFFINI. A review of perturbations around Schwarzschild black holes has been presented by S. CHANDRASEKHAR, while R. PENROSE has analysed some of the properties of the formations of horizons in space-times and E. T. NEWMAN on aspects of rotation in relativistic theories. Properties of the Tomimatsu-Sato solutions have been given by H. SATO, while effects of spin interactions in gravitational theories have been presented by T. DAMOUR, R. F. O'CONNELL and H. OKAMURA, and finally considerations on some ergosphere processes by T. PIRAN. An extensive review of the current understanding of the late stages of evolution of stars with special emphasis on the formation of neutron stars and black holes has been made by W. ARNETT. The physics of neutron stars, their magnetospheres and internal structure has been reviewed by V. CANUTO, while L. PIETRONERO has presented some technical details in the proof of the upper limit to the critical mass of neutron stars. The role of neutrino physics in supernovae and in the formation of neutron stars has been reviewed by S. COLGATE, S. TSURUTA and J. WILSON. Finally J. WILSON has presented some recent progress in the numerical analysis of relativistic magnetohydrodynamics and W. KUNDT some progress in the analysis of pulsar magnetospheres.

In the phenomenological papers R. SUNYAEV has presented an extensive review of the relativistic plasma physics relevant to model making of binary X-ray sources, while their general evolution and astrophysical setting has been presented by E. VAN DEN HEUVEL and J. HEISE. Some of the aspects more specific to black-hole accretion have been summarized by M. REES. Finally some considerations on pulsar magnetospheres and on Hercules X-1 have been presented by M. FUJIMOTO and G. BÖRNER.

We would like to express our gratitude to the Italian Physical Society and to its President, C. CASTAGNOLI, for having given us the opportunity of holding this summer school in the « Enrico Fermi » series. The success of the school was enhanced by the expertise of the entire staff of the Italian Physical Society and especially of Dr. G. WOLZACK to whom we are deeply thankful.

The publication of the proceedings has been made possible by the publishing board of the Italian Physical Society. We are particularly grateful to them and to P. PAPALI for their constant attention. We would like to express our thanks to the European Space Agency and its Director General R. GIBSON and to the Marchesa B. FRESCOBALDI for sponsoring the school: their help has made the school much more pleasant and successful. Finally our warm thanks go to the scientific secretary of the school, Dr. A. TREVES, to the lecturers, to all the participants for their enthusiastic participation.

R. GIACCONI
R. RUFFINI

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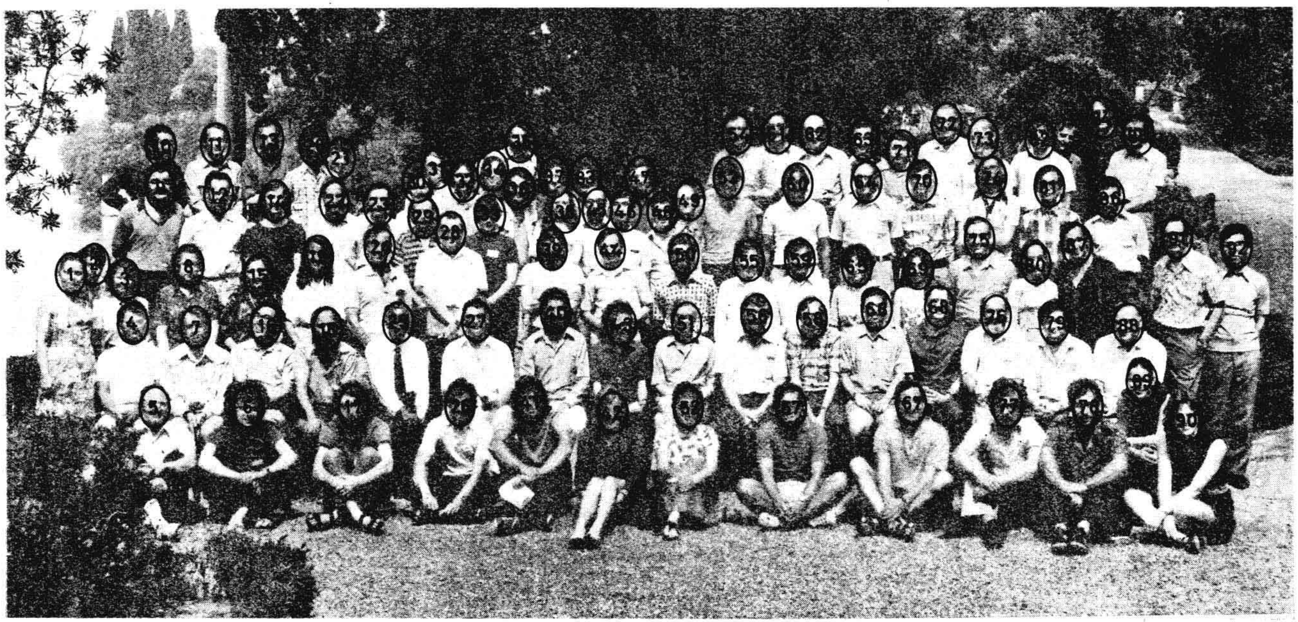

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