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XXXV CORSO

Astrofisica delle alte energie

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XXXV CORSO

a cura di L. GRATTON
Direttore del Corso

VARENNA SUL LAGO DI COMO
VILLA MONASTERO
12 - 24 LUGLIO 1965

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High-Energy Astrophysics

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PREFACE.

L. GRATTON

These lectures on High-Energy Astrophysics appear more than one year after they have actually been delivered at Varenna. This lapse of time may appear somewhat too large in such a rapidly growing subject. However, the main reason for the delay was just this rapid growth; indeed some of the Authors were so desirous to include their own latest contributions to the field, that they were reluctant to send their manuscripts. Obviously this could not go on indefinitely and the Editor had finally to put a dead line, which proved to be about June 1966.

The result was that some of the papers, especially those concerned with the observational facts, were brought up to date to the middle of 1966, and this certainly adds much value to the book. Among the few important results which could not be included, let me quote here only the recent identification of the source *Sco* X-1 with a peculiar optical object, probably an *ex-Nova*, by a group of researchers, among whom some of the contributors to this volume.

On the other side, it seems that no decisive advances on the theoretical side of the problems have been made between June 1965 and the middle of 1966; hence in this connection we feel confident that the reader will find reasonably complete and up to date information.

The time spent at Varenna will certainly be remembered by all who were there as a very happy one. For this let me express here my best thanks to everybody, to the teachers for their splendid lectures, to both teachers and students, for the lively discussions which followed each lecture and lasted often during the promenades along the lake and during many after-sessions around tables scattered with espresso-cups and glasses of beer and fine Italian wine (how many bright ideas were suggested by it and perhaps are still on their way to materialization!).

Finally a warm thank is also due to the Italian Society of Physics and its efficient secretary, Prof. GERMANÀ, to whose untiring efforts a large part of the success of the E. FERMI Courses is due.

SOCIETÀ ITALIANA DI FISICA

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XXXV CORSO - VARENNA SUL LAGO DI COMO - VILLA MONASTERO - 12 - 24 Luglio 1965

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High-Energy Astrophysics.

L. GRATTON

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1. – Introduction. - High-energy astrophysics.

E ogni permutanza credi stolta,
Se la cosa dimessa in la sorpresa,
Come 'l quattro nel sei non è raccolta. (*)
DANTE, *Paradiso*, Canto V, 58-60.

The history of the last hundred years shows that on several occasions the astrophysical demand of sources of very large quantities of energy has presented exceedingly difficult problems to physics, which could be satisfactorily solved only when some important advance in the very fundaments of physics became available. For instance, when it became evident that the life of the Sun was by some order of magnitude larger than 10^7 y, it was impossible to explain its present rate of radiation, until the discovery, mainly by BETHE (following earlier suggestions by ATKINSON and HOUTERMANS), of the thermonuclear reactions leading to the synthesis of He in the solar interior.

The equivalence of mass and energy predicted by the theory of relativity, while providing an enormous amount of energy stored in material bodies, has put also a definite upper limit to it; indeed, if $\mathcal{M}$ is the mass contained in a certain volume, measured from its gravitational effect upon an external test particle, the energy which may be extracted from it by any conceivable process cannot evidently exceed $\mathcal{M}c^2$.

(*) And let him deem every permutation foolish, if the thing laid down be not contained in that which is taken up, as four in six.

As a matter of fact, with the sole exception of the process of annihilation of particles and antiparticles, all known physical processes lie far below this limit. The most effective nuclear process (the synthesis of one ^{56}Fe atom out of 56 H atoms) cannot extract from a body (consisting initially of pure hydrogen) more than the 0.88% of its rest energy.

Recent astrophysical evidence had led to suspect that in some cases the limit set by the relativity theory is much more closely approached. In other words some observations suggest that from certain regions of space large amounts of energy are released under the form of electromagnetic waves and others, the total quantity released being perhaps a considerable fraction of $\mathcal{M}c^2$, if $\mathcal{M}$ is the total (gravitational) mass which under any reasonable assumption we can admit to have been initially enclosed in the body from which the observed phenomena originate. It seems thus that a more efficient mechanism than nuclear reactions has to be considered.

Some different mechanism must be invoked any way in the case of supernovae outbursts, since it is generally agreed that supernovae are stars whose matter has reached the end of nuclear evolution, that is the stage at which all possible nuclear reactions are exothermic.

Gravitational collapse has been suggested as a possible mechanism by means of which a quantity of energy can be released which may be a considerable fraction of the rest energy of a body. Whether this mechanism works in all cases is however by no means certain.

In all these cases the astrophysical results point towards rather unstable phenomena, suggesting explosive or, at any rate, very violent events. This is in contrast with the evolution of normal astrophysical objects, which occurs in a slow peaceful way. Compare, for instance, the rate of energy release in the Sun, about 2 erg s^{-1} g^{-1}, with that of a supernova, at maximum brightness, which is probably 10^9 times larger. In a similar way, although the masses of quasistellar radio sources are very uncertain, the present evidence suggests that their emission rate per gram is at least 10^5 times larger than that of an average galaxy.

The words « High-Energy Astrophysics » as a general title for those developments which deal with these phenomena, are thus meant to indicate not merely processes in which large amounts of energy are involved, but, mainly, those in which the rate of energy release per second and gram is very high as compared with the more usual processes going on in normal stars and galaxies.

The problem of finding a suitable energy source, that is a physical process or some physical processes, by means of which large amounts of energy stored in rather small volumes are released under the form of electromagnetic waves or others, is however only one of the difficulties. Another equally important problem arises from the fact that, if our interpretation of the low-frequency emission, and perhaps also of a part of the optical spectrum is correct, a very important fraction of the electromagnetic spectrum is due to synchrotron radiation, that is to magnetic bremsstrahlung. In turn this is indicative of the existence of magnetic fields and of a large quantity of high-energy (relativistic) electrons, whose total energy is itself a very considerable fraction of $\mathscr{M}c^2$, if the initial mass $\mathscr{M}$ is to be kept within reasonable limits.

How such a large amount of energy has been transferred into this high-energy plasma, whichever was the form under which it was stored in the initial body? Is there any connection between the high-energy particles associated with the radio emission from these bodies and primary cosmic rays?

To find a suitable mechanism of acceleration of individual particles to relativistic energies seems an exceedingly difficult problem; perhaps even more difficult than that of the energy source itself. Indeed, generally speaking, the tendency in Nature is towards a fragmentation of any amount of energy in fractions as small as possible; as a consequence by far the largest quantities of energy permanently concentrated in single units are the rest energies of baryons. Of course, this is due to the very low average energy density of the universe; the breaking of the rest energy of baryons into smaller units being prevented only by the law of conservation of baryons.

A mechanism which concentrates very large amounts of energy in single particles, is thus in a way something which is going against this general tendency. In other words it produces a very large decrease of entropy in a certain system which must be accompanied by a correspondingly larger increase in another (interacting) system, if we wish to respect the 2nd principle of thermodynamics. The kind of the interaction constitutes a very hard problem indeed and it may be that we have to seek the solution in a completely different and unexpected direction.

Parallel to all these considerations goes the problem of the evolutionary course followed by the objects involved in the processes of high-energy astrophysics. Are they completely different objects from ordinary stars and galaxies or simply peculiar evolutionary stages of these more common objects? If so, how do they fit into the general evolution of stars and galaxies?

Of course the urgency of introducing evolutionary ideas comes from the explosive or short-lived character of these objects. After all, we can hope to understand the structure of a star (we do in fact understand it) or of a galaxy even without knowing much about their origin and their final fate; the reason is that their life is very long (from 10^8, for the shortest-lived stars, to 10^{11} years) compared with the time necessary to restore dynamical equilibrium. But the lives of a supernova and of a quasi-stellar radio source, as such, are so short that the problem of their evolution cannot be ignored from the very beginning. In other words the problem is essentially a dynamical one and must be stated as such.

2. – Supernovae, neutron stars and gravitational collapse.

These our actors,
As I foretold you, were all spirits and
Are melted into air, into thin air:
And, like the baseless fabric of this vision,
The cloud-capp'd towers, the gorgeous palaces,
The solemn temples, the great globe itself,
Yea, all which it inherit, shall dissolve
And, like this insubstantial pageant faded,
Leave not a rack behind.

W. SHAKESPEARE, *The Tempest*, Act IV, 148-156.

The detailed study of the different problems will be the subject of the following lectures. I will, therefore limit myself to two astrophysical problems, giving a general sketch from an historical point of view, mainly for the benefit of the students who are not especially acquainted with them.

Supernova outbursts have been known since several centuries, but for a long time they have been mistaken with ordinary novae. The first realization that they implied much larger amounts of energy (by many orders of magnitude) was due to ZWICKY, who also suggested that the outburst might be connected with the collapse of a more or less ordinary star into a highly condensed state in which its matter consisted essentially of a gas of neutrons (ZWICKY 1958).

The theory of neutron stars was, thus, associated from the beginning with the outbursts of supernovae. After the pioneer work by LANDAU (see LANDAU and LIFSHITS 1959), OPPENHEIMER and others (OPPENHEIMER and VOLKOFF, 1939), it was revived more recently by CAMERON (1959), HAMADA and SALPETER (1961) and others, mainly following the work of BURBIDGE, BURBIDGE, FOWLER and HOYLE (1957) who showed that a star which has reached the end point of its nuclear evolution should undergo a violent collapse; important contributions are due also to CHIU (1965).

In the case of the supernova outbursts, it seems that the primary energy source is not a difficulty; gravitational collapse of a body of more or less the Sun mass provides a sufficient amount of energy, the binding energy of the final body, which is radiated away during the collapse. If the final product is a zero-temperature neutron star the energy released is amply enough.

The discovery by ROSSI and his coworkers (GIACCONI, 1964) and by FRIEDMAN (1965) of a number of discrete sources of X-rays, almost certainly galactic, one of which is coincident with the Crab Nebula (the famous remnant of the 1054 Supernova), connected quite naturally neutron stars with these sources. Although it seems now that the connection, if it exists, cannot be too direct, the idea cannot be completely dismissed. We shall hear more about it during these lectures. However the most recent work by BAHCALL and WOLF (1965 *a*, *b*), FINZI (1965) and others makes it rather improbable that we shall ever be able to observe a neutron star through its direct radiation. We may quote on this connection also recent contributions by MORRISON and SARTORI (1965), DE SABBATA and GUALDI (1965) etc....

A problem of enormous theoretical interest is associated with a neutron star or, more generally, with a cold body at the end of its nuclear evolution. It was known since Oppenheimer's work that no equilibrium state exists for a neutron star if its mass exceeds a certain critical value somewhat less than one solar mass. It was also known that for a smaller mass there exist two equilibrium solutions, one stable and the other unstable, the latter corresponding to a more centrally condensed configuration with a lower energy content. In other words, the stable solution is, really, « metastable »; given a sufficiently strong perturbation the body will collapse into the unstable state and, from this, the collapse will continue indefinitely. An indefinite collapse will ensue anyway in the case of a mass larger than the critical mass, since no equilibrium is possible.

It is maintained by WHEELER (1964) and others that, although this cannot be rigorously proved, no equation of state of the neutron matter can prevent the collapse of the body inside its own Schwarzschild's singularity, a fact which is described some times as the « squeezing of matter out of existence ». Although the question may have no practical importance, it is nevertheless very important in principle. It might well be that by such considerations as these, we may be led to modify some of our basic physical laws, like the field equations of general relativity from one side, or the conservation of baryons from another.

However the possibility that the collapse might be halted by a suitable equation of state cannot be ruled out entirely. This point was discussed by CHIU (1965), GRATTON and SZAMOSI (1964) and by MARX and NÉMETH (1965); but it must be avowed that we ignore completely the behaviour of matter compressed to such high densities (well beyond nuclear densities).

Some exploratory work on this field is due to BAHCALL and WOLF (1965*a*) and also to HAGEDORN (1965); it seems that at very large densities the concept of individual particles fails. The thermodynamics of hadrons (strongly interacting particles) leads to a mass spectrum which is entirely different from its free-particle analogue. Thus, the independent-particle model may, at best, give only a very rough suggestion of what might happen.

Several recent developments have also appeared on the dynamics of the collapse and will be revised in these lectures. After OPPENHEIMER and SNYDER'S (1939) early work, important contributions have recently been made by BURBIDGE, BURBIDGE, FOWLER and HOYLE (1964), MCVITTIE (1964), MISNER and SHARP (1964), BONDI (1964), MAY and WHITE (1965) and FIR-

MANI (1965). However the most detailed computations (based on classical mechanics) are due to COLGATE and WHITE (1964).

But speaking as an astrophysicist, I would like to venture the opinion that the most urgent problem is to extract from the spectra of supernovae all the information they contain. At present practically all we know about an individual supernova comes from the study of the Crab Nebula (WOLTJER 1958), which is being observed nine centuries after its outburst and might not be typical. It is well possible that a complete interpretation of the spectrum of a Supernova near maximum might give a clue as to the mechanism of the collapse and to the acceleration of (individual) electrons to relativistic energy which is required to explain the present synchrotron radiation of the Crab Nebula.

3. – Radiogalaxies, quasi-stellar radio sources and related objects.

There was Chaos at first, and Darkness and Night,
and Tartarus vasty and dismal;
But the Earth was not there, nor the Sky, nor the Air,
till at length in the bosom abysmal
Of Darkness an egg, from the whirlwind conceived,
was laid by the sable-plumed Night.
And out of that egg, as the Seasons revolved
sprang Love, the entrancing, the bright,
Love brilliant and bold with his pinions of gold,
like a whirlwind, refulgent and sparkling.

ARISTOPHANES, *The Birds*, 693-697.

Ordinary galaxies, like our own or the Andromeda Nebula, do not radiate very strongly in the radio-frequency range; besides the 21 cm emission due to interstellar hydrogen, they possess a rather faint continuous which is interpreted as synchroton radiation from an extended halo of relativistic electrons moving in the general galactic magnetic field.

It has been found, however, that there exists a number of galaxies which are very strong radio-emitters; some very-well-known examples are the radio-sources *Centaurus* A (connected with NGC 5128, a peculiar elliptical nebula), *Cygnus* A, *Virgo* A (connected with M 87) etc. In general the galaxies associated with these radio-sources are very bright giant galaxies showing some peculiarities like dark bands rather exceptional for their types, bright « jets » whose light is often strongly polarized, or other similar uncommon features.

The radio-flux does not come from the same volume as the optical light; most often it is emitted by two sources more or less symmetrical relative to the optical object and far apart from it along its axis of rotation. It has been also remarked that radiogalaxies occur mostly as single objects or in poor