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# Astronomy

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## Abstract

## Full Text

*Astronomy*

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# THE FATE OF A STAR AND THE RELEASE OF GRAVITATIONAL ENERGY DURING ACCRETION

It is well known that cold matter cannot resist the compressive action of gravitation if its mass is greater than the mass of the Sun. This result was obtained by Oppenheimer and Volkoff ([1]) in 1938 in considering a degenerate neutron gas in the Einstein theory of gravitation ( “general theory of relativity” ) and has entered the textbooks ([2]). Qualitatively, the result is not changed under any assumptions about the interaction of elementary particles at high density.

General relativity radically changes the intuitive picture of the dynamics of compression. In the classical theory an infinite density is reached in a finite time; one might think that after this an expansion would occur, or that a shock wave would arise, propagating outward from the center and ejecting part of the matter.

As Oppenheimer and Snyder ([3]) showed, general relativity leads to the conclusion that an infinite density is indeed reached in a finite proper time (measured by an observer moving together with some particle of the star). However, in transmitting signals from the star to an external observer located outside the gravitational field of the star, it is necessary to take into account the change in the scale of time. The red shift of lines emitted from the surface of the star is a special case of this change in the rate of time. It turns out that for an external observer, asymptotically as $t \to \infty$, the outer surface of the star only reaches the so-called gravitational (Schwarzschild) radius $r_g = 2GM/c^2$. For each particle, for example the central one, one can determine the moment when this particle must emit a signal in order that this signal reach the external observer at $t \to \infty$. In this sense one may speak of the gravitational self-closure of a contracting star ([4]).

At the moment of emission of the signal, the density in each particle is less than the characteristic value

$$\rho_g = \frac{3M}{4\pi r_g^3} = \frac{3}{32\pi}\frac{c^6}{M^2G^3} = 1.8 \cdot 10^{16} \left(\frac{M}{M_\odot}\right)^{-2} \frac{\text{g}}{\text{cm}^3}.$$

Consequently, the attainment of infinite density in the course of compression

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is unobservable; the acquisition of information ends long before that moment. Still less does the question of what will happen after $\rho = \infty$ have any meaning.

All these results remain valid when pressure is taken into account ([5]), and also for hot matter. The problem of the existence and stability of mechanical equilibrium in the presence of pressure and gravitation should be considered at fixed entropy of the matter. Equilibrium corresponds to a minimum of the total energy at a given entropy (and, naturally, at a given number of conserved particles—baryons). In the course of rapid compression it may also be assumed that the entropy is conserved.

For each value of the entropy $S$ there is a series of equilibrium configurations of hot gas (stars) differing in mass $M$; such configurations exist, however, only for masses below a critical one. The value of the critical

the mass $M_c$ the larger, the greater the entropy $S$, $M_c = M_c(S)$. For $S = 0$, $M_c = M_c(0) \simeq M_\odot$. Stars with $M > M_\odot$ can be in a state of mechanical equilibrium insofar as they are hot and insofar as, at equal density, the pressure of the hot matter is greater than the pressure of cold matter([6]).

Consequently, the final stage in the evolution of any nonrotating star whose mass considerably exceeds the mass of the Sun is inexorable contraction—collapse.

The luminosity of a hot star during collapse, because of the effect of gravitational self-closure, dies away very rapidly exponentially, falling by a factor $e$ over a time of order $r_g/c$, i.e. $10^{-4}$ sec for $M \sim 10M_\odot$. Consequently, collapsed stars must be dark bodies whose interaction with the surrounding medium is limited by their gravitational field. Since the radiation, and hence the loss of mass during collapse, are insignificant([4,7]), the gravitational field of a collapsing star at a large distance is almost no different from the field of the same star before contraction. The question of what fraction of all nucleons in the Universe is currently in dark collapsed stars was posed in ([8]). From considerations connected with the age of the Universe, one could obtain only the inequality for the total density $\bar{\rho} < 2 \cdot 10^{-28}$ g/cm$^3$, whereas the density in normal, visible stars is $\rho \simeq (0.3 \div 1) \cdot 10^{-30}$ g/cm$^3$. Hoyle, Fowler, and Burbidge([7]) decisively raised the question of the existence of a large number of dark stars. According to their estimate, the mass of all such stars is several times greater than the mass of luminous stars, which is close to the upper limit according to ([8]). Interest in the catastrophic contraction of stars increased in connection with the discovery of optically bright distant radio sources([9,10]) and Hoyle' s hypothesis([11]) that these sources are superstars with masses of order $10^8 M_\odot$. The source of energy of powerful radio galaxies had until recently not been clear; the ideas of annihilation of matter and antimatter, of collisions of galaxies, and of the simultaneous explosion of many supernovae proved untenable. How does the contraction of superstars lead to the release of the required gigantic quantities of energy? According to ([7]), the contraction is accompanied by oscillations, the density reaches $10^{30}$ g/cm$^3$, and at this instant of maximum density ultrarelativistic particles are ejected. One cannot agree with this point of view, not only

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because the halt at $\rho_m = 10^{30}$ g/cm$^3$ depends on a hypothetical $C$-field, which has very strange properties([7],[12] ). In reality, for an external observer the growth of density asymptotically stops at the quite modest value of order $2 \div 200$ g/cm$^3$ (for $M = 10^8 \div 10^7 M_\odot$) by virtue of gravitational self-closure.

In the present note another mechanism of energy release is considered, one connected with the fall of the outer masses in the gravitational field of the contracting star.

On approaching the gravitational radius, the velocity of a freely falling particle approaches the speed of light.

The collision of two particles at a distance of order (not greater than!) the gravitational radius occurs with a relative velocity of order $c$. Consequently, in a collision the radiation energy of relativistic particles may be $\alpha mc^2$; the energy carried away to infinity is less: because of the redshift and the geometrical factor, part of the radiation and of the particles falls onto the star. The energy output outward is equal to $\alpha\beta mc^2$, where $m$ is the mass of the particle, $\alpha < 1$, $\beta < 1$. This product reaches a maximum of order $0.1mc^2$ for a collision at $r = 1.5r_g$. It is essential that the colliding particles have different angular-momentum vectors relative to the star; the quoted numbers refer to $\vec{M}_1 = -\vec{M}_2$. If collisions occur rarely, then for a given distribution of particles over velocities far from the star the energy release is proportional to the collision cross section. For a large cross section, when the mean free path becomes small in comparison with the size of the star, collisions order the motion of the particles, and in this case it is necessary to pass to a hydrodynamic description of the motion. It then turns out that, in spherically symmetric motion, the gravitational energy is mainly converted—

is converted into the kinetic energy of radial motion; the amount of energy that can be radiated is a negligibly small fraction of the rest mass of the falling matter.

However, if a stream of matter impinges on the star with a superluminal directed velocity far from the star, the picture of the motion changes sharply. On the side of the star opposite to the direction from which the stream comes, a stationary shock wave arises. Near the star the change in velocity at the wave front is of order $c$, and an appreciable fraction $mc^2$ of the matter compressed by the wave is radiated. In stationary hydrodynamic motion, by Bernoulli' s theorem, it is impossible for even a small part of the matter to be ejected to infinity with a velocity greater than the initial velocity far from the star. However, at the moment when the cloud of matter approaches the star, surrounds it, and collapses on the far side, the motion is nonstationary, and a cumulative ejection of part of the matter with a velocity of order $c$ is possible.

Let us note, in conclusion, that the "particles" discussed above need not be atoms and molecules, but may be clumps of plasma with a frozen-in magnetic field; then the formation of relativistic electrons in the collision is especially probable. In considering a stream of matter from afar, one should apparently

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not imagine the interstellar gas and dust with $\bar{\rho} = 10^{-25}$ g/cm$^3$, which would give a small power.

As the infalling material one may imagine the matter of the second star during the collapse of the first star of a close binary system. This may be that part of the envelope of the collapsing star itself which was ejected just before the moment of gravitational self-closure: along with matter acquiring a hyperbolic velocity, part of the ejected matter may remain in reserve on distant but closed orbits.

In its most general form, the idea that falling in a strong gravitational field can serve as a source of radio-emission energy was expressed by I. S. Shklovskii [13].

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*Note: Figure translations are in progress. See original paper for figures.*

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