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THE ROLE OF WHITE HOLES IN ASTROPHYSICS

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INTRODUCTION

Many astrophysical phenomena involve high energy quanta or particles. Direct observations of cosmic rays have revealed the existence of energetic particles with energies upwards of 10^{20} eV. Satellite and balloon observations have demonstrated that sources X-rays and gamma rays exist in the universe. The extragalactic radio sources require for their explanation the phenomenon of synchrotron emission, i.e., the emission of radiation by fast moving electrons in a magnetic field. While the astrophysicist is able to account for many of these high energy phenomena by postulating the existence of such energetic particles and quanta, he is more often than not, at a loss to account for their primary sources.

To some extent the high energy astrophysicist is in a similar predicament as his cosmological counter-part, the big-bang theorist. In the big-bang theory the origin of the universe through a primordial explosion is postulated. Little progress has been made in the several decades since its inception, in understanding the nature of this explosion, although the subsequent behaviour of the universe is comparatively well charted. The big-bang cosmologist may (not very justifiably) shirk the responsibility of explaining the nature of the big-bang on the grounds that it was a unique event which took pace over 10^{10} years ago. The high energy astrophysicist cannot do the same; for the phenomena encountered by him are of shorter timescales and in some cases, of recurring nature. A radio source is not expected to last much longer than $\sim 10^6$ years. The cosmic rays have life-times estimated in the range of 10^6 - 10^9 years. The X-ray sources, on the other hand show characteristic time scales of the order of a year or considerably less, while the gamma ray bursts are over in a matter of seconds. It is therefore necessary to think of a phenomenon which would result in the generation and supply of high energy particles and quanta of relevance to high energy astrophysics.

The white hole is one such phenomenon. It is essentially a system where matter is pouring out from a highly dense state. In the initial state the system may be inside its event horizon, although this does not prevent an external observer from receiving light signals or particles emitted from its surface. In this sense the situation here is opposite of that in a black hole which is believed to have formed from the gravitational collapse of a massive object. Unlike a black hole, a white hole is readily visible.

In this lecture I propose to review the recent work on white holes with reference to the above mentioned astrophysical problems. I shall begin by a general discussion of what a white hole is. I shall then discuss a simple canonical model within the framework of general relativity. Some astrophysical consequences of such a model have been worked out. I will refer to these briefly. Finally I shall briefly review some of the objections to the concept of white holes and how they have been circumvented.

WHAT IS A WHITE HOLE?

There are several scenarios for the white hole. In 1965 Neeman [1] and Novikov [2] had independently suggested the idea of the 'delayed bang' or the 'lagging core'. In this concept it is assumed that the big-bang universe did not explode 'simultaneously' at the cosmic time $t = 0$, but that certain parts of it remained dormant until they exploded at a later instant $t > 0$. The very bright objects called the quasi-stellar objects were identified with these and presumed to have derived their extreme brightness from the delayed explosions.

In 1964, Faulkner et al. [3] had calculated the blueshift from the surface of a compact object exploding from a space-time singularity. This blue shift could be considered as the main reason for the brightness in the lagging core type models. In the following section I shall elaborate further on the Faulkner-Hoyle-Narlikar model.

Hjellming [4] in 1971 proposed a somewhat different variant. He considered the collapse of a black hole into the space-time singularity to be followed by an explosion of a white hole from the singularity into another topologically connected universe. While this idea removed the necessity of postulating a beginning for a white hole, it introduced the complication of having several universes linked to one another by a black hole and a white hole.

A somewhat different way of linking the black holes with white holes was provided by Hoyle and Narlikar [5] through their conformal gravitation theory. In this theory the space-time singularity of the big-bang universe or in a black hole or a white hole receives the interpretation that it is a region of a conformally transformed non-singular manifold where the inertial masses m of material particles vanish. The surfaces $m = 0$ in this manifold become singular in the usual way of general relativity if one insists on using the conformal frame m = constant. This has been discussed in detail by Kembhavi [6]. Thus a closed $m = 0$ surface in a non-singular manifold manifests itself as a combination of two pairs of black holes followed by white holes. For elaboration of this idea see Hoyle [7].

Within the orthodox general relativity it does not seem possible to control and reverse the gravitational collapse of a massive object once it has crossed into its event horizon (see Hawking and Ellis [8]). There is a loop-hole in the usual singularity theorems, however, which suggests that if the energy condition is violated the singularity may be prevented. Indeed there are examples of this, in negative energy fields and tachyons. The

C-field of Hoyle and Narlikar [9] is a negative energy zero rest mass scalar field and its introduction reverses the collapse of a massive object without attaining singularity (see Narlikar [10]). Such an object will have the appearance of a white hole in its expanding phase.

These examples indicate how the white hole may arise, not just in classical general relativity but also in other theories. In this lecture my discussion is confined to classical ideas only. The injection of quantum theory into gravitation, especially near space-time singularity or near black holes has led to many fruitful, if somewhat speculative ideas. Rightly or wrongly, I have decided not to include them in the present discussion.

THE CANONICAL WHITE HOLE

The simple model considered here is that used by Faulkner et al. [3] and later by Narlikar and Apparao [11] . We will assume the white hole as a spherical object of uniform density and zero pressure in the comoving frame of the outward moving particles, emerging from a space-time singularity and satisfying the equations of general relativity. The line-element of the space-time within the object is described by the Robertson-Walker form

$$ds^2 = c^2 dt^2 - S^2(t)\left\{\frac{dr^2}{1-\alpha r^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right\}, \qquad (1)$$

where $r(\leq r_b)$, θ and ϕ are the comoving co-ordinates of a constituent particle and t the 'simultaneous' time-coordinate. The spaces t = constant are homogeneous and isotropic, for $r \leq r_b$. The function $S(t)$ and the parameter α satisfy the relations

$$\alpha = \frac{2GM}{c^2 r_b^3}, \qquad (2)$$

$$\dot{S}^2 = \alpha c^2 \left\{\frac{1-S}{S}\right\}. \qquad (3)$$

Here G = Newtonian gravitational constant, c = speed of light, M = the gravitational mass of the white hole and r_b = its comoving radius. The solution is time symmetric. For $\dot{S} < 0$ it represents contraction (black hole and for $\dot{S} > 0$ it represents expansion (white hole). We are concerned here with $\dot{S} > 0$. The 'maximum size' is attained when $\dot{S} = 0$, i.e., when

$$t = t_0 \equiv \frac{\pi}{2c\sqrt{\alpha}}. \qquad (4)$$

The space-time exterior to the object will be presumed empty and hence describable by the Schwarzschild line element:

$$ds^2 = \left(c^2 - \frac{2GM}{R}\right)dT^2 - \left(1 - \frac{2GM}{c^2 R}\right)^{-1} dR^2 - R^2(d\theta^2 + \sin^2\theta\, d\phi^2). \qquad (5)$$

A typical exterior Schwarzschild observer has constant R, θ, ϕ co-ordinates. At the boundary of the object we must have

$$R = R_b \equiv r_b S(t). \qquad (6)$$

Thus an observer on the boundary has increasing Schwarzschild R-co-ordinate. At the same θ, ϕ, such an observer will appear to be approaching the exterior Schwarzschild observer. Does this result in a blueshift of light from the surface out to large radial distances? The answer is not obvious since the outgoing light also suffers gravitational redshift.

Detailed calculations of [11] show that a frequency ν_0 of emission from the surface becomes a frequency ν at large distance ($R \gg 2GM/c^2$) away from the white hole, where

$$\frac{\nu}{\nu_0} = \frac{\sin(\eta + \eta_s)}{\sin \eta}. \tag{7}$$

The parameters η, η_s are related to S(t), by the following relations:

$$S(t_e) = \sin^2 \eta \quad , \quad S(t_s) = \sin^2 \eta_s , \tag{8}$$

where t_e = epoch of emission and t_s = epoch when the white hole boundary crosses the Schwarzschild barrier.

Thus there is blueshift if the emission epoch is early enough to satisfy $0 < \eta < \frac{1}{2}(\pi - \eta_s)$. At subsequent epochs the signals are red-shifted. Note that blueshifts are possible even for signals emitted after the white hole surface has crossed the Schwarzschild barrier, provided $\eta_s < \pi/3$, i.e., provided

$$\frac{2GM}{c^2 r_b} < \frac{\pi}{3}. \tag{9}$$

For the distant Schwarzschild observer, T is very nearly the proper-time co-ordinate. If we measure T from the instant the signal emitted at $t_e = 0$ reaches this observer, we find that the respective periods of blue shift and redshift are given by

$$T_B = t_0 \int_0^{(\pi - \eta_s)/2} \frac{4 \sin^3 \eta}{\pi \sin(\eta + \eta_s)} d\eta , \tag{10}$$

$$T_R = t_0 \int_{(\pi - \eta_s)/2}^{\pi/2} \frac{4 \sin^3 \eta}{\pi \sin(\eta + \eta_s)} d\eta . \tag{11}$$

T_B and T_R are comparable to t_0 except when η_s is very close to 0 or $\pi/2$. For example, for $\eta_s = \pi/4$, $T_B/t_0 \sim 0.39$ and $T_R/t_0 \sim 0.57$.

Interesting results are obtained for the spectrum of the white hole as seen by the external observer. Suppose first that the white hole has a constant luminosity L in a monochromatic radiation of frequency ν_0 in the rest frame of the surface. Writing $E_0 = h\nu_0$, $E = h\nu$, where h is the Planck constant, the differential photon number spectrum at the external observer is given by

$$N(E)\,dE = \frac{L t_0}{\pi^2 R_1^2} \frac{E_0^2 \sin^3 \eta_s \, dE}{(E^2 + E_0^2 - 2EE_0 \cos \eta)}$$

$$\cong (\text{constant}) . \frac{dE}{E^4} \quad \text{for } E \gg E_0 . \qquad (12)$$

Thus a monochromatic spectrum at source looks like a steep inverse power law spectrum at the observer. Also, in (12) not all quanta arrive at the same time. The quanta which were emitted earlier, arrive earlier, and with larger blueshift. Thus the spectrum softens with time.

Since more dramatic effects are expected from the early high blueshift stages, we will consider the general case of emission for $t_e \ll t_o$. Let $L(\nu_o, t)d\nu_o\,dt$ denote the energy in the frequency range $(\nu_o, \nu_o + d\nu_o)$ emitted in the time interval $(t, t + dt)$ from the surface. Then the flux of radiation crossing per unit area at the remote observer, in unit time and in the frequency range $(\nu, \nu + d\nu)$ is given by $S(\nu, T)d\nu$, where

$$S(\nu, T) = \frac{1}{4\pi R^2}\left(\frac{T_0}{T}\right)^{1/4} L\left(\nu \frac{T^{1/4}}{T_0^{1/4}}, \frac{4}{3} T_0^{1/4} T^{3/4}\right). \qquad (13)$$

Here R is the Schwarzschild radial co-ordinate for the external observer.

The emission of material particles is qualitatively similar. They behave like photons in the sense that their energies are lifted 'up' by the white hole if they are emitted early enough. Of course, if they leave the surface in a radially outward direction with speeds comparable to the speed of light, their behaviour is asymptotically given by the above formulae for the photons.

Dhurandhar [12] has investigated the trajectories of tachyons in white holes, with some curious results. A tachyon emitted at $t = 0$ and starting at $r = 0$ begins to overtake the material particles of the white hole. However, it loses energy because of travelling through an expanding space - analogous to the redshift of light in the expanding universe. If it loses all its energy before leaving the white hole, it turns back in time, although continuing to move forward in r-coordinate. It can still escape if its r-coordinate exceeds r_b before $t \rightarrow 0$! All these different possibilities depend on the initial conditions of tachyon emission and on the white hole parameters.

APPLICATION TO ASTROPHYSICS

The two outstanding characteristics of white holes are their explosive and transient nature. I will now describe some astrophysical phenomena where white holes could be the primary causes because of these properties.

(a) Radiation from the nuclei of Seyfert galaxies - Seyfert nuclei are observed to emit infrared radiation up to $\sim 10^{45}$ erg s^{-1}. It has been suggested that this radiation is due to the dust which has been heated by ultraviolet radiation emanating from the galactic centre. X-radiation is also observed from the Seyferts [13] and it has been suggested by Silk [14] that the Seyferts may act as sources of the observed X-ray background. These facts and theories have been linked up by Narlikar and Apparao [11] in the following way.

Although in the simplest case considered above the radiation at $E \gg E_0$ has the $E^{-4}\,dE$ from the observed differential spectrum of X-ray background is $\sim E^{-2}\,dE$. A flattering of the primary white hole spectrum to the observed form can be achieved in the range 0.2 - 1 keV by the absorptive effect of the surrounding gas. Further, the primary spectrum $E^{-4}\,dE$ suggests that $\sim 10^{45}$ ergs s^{-1} in the ultraviolet (required for conversion to the infrared through dust) corresponds to $\sim 10^{41}$ ergs s^{-1} in the X-rays. This is of the right order as estimated by Silk [14] for a typical X-ray source to account for the X-ray background.

(b) Transient X-ray sources - X-ray sources lasting for short durations ranging from days to a few years can be related to a white hole source. Narlikar and Apparao [11] have considered various possible shapes for $L(\nu_0, t)$ to see whether the observed decay curves agree with the corresponding $S(\nu, T)$. There is a broad qualitative agreement which can be improved (or the proposed scenario disproved) only by more data.

(c) Gamma ray bursts - There is a possibility of invoking the white holes for understanding gamma ray bursts lasting for short duration (1-100 s.). The steepness of the spectrum and its softening with time are as expected on the white hole model.

It is interesting to see how a time-independent luminosity in the comoving frame can lead to pulses with double structure. If $L(\nu_0, t)$ does not depend on time t but has two well separated peaks in ν_0, each peak appears as a pulse at a different T-time to the distant observer using a detector sensitive to a given range of frequencies. The pulse arriving first is more blueshifted and hence corresponds to the peak of lower frequency. By varying the observing frequency ranges the arrival times of pulses can be altered. The model is therefore capable of being tested.

It should be noted that the white holes postulated in the above three cases are of different masses. From energy considerations it is estimated that the remnant after a gamma-ray burst will be $\sim M_\odot$, whereas the transient X-ray sources will be of the order of a few solar masses. The masses of white holes at the nuclei of Seyfert galaxies may be as high as $\sim 10^5\, M_\odot$.

The rate at which a white hole explodes determines the energy spectrum of the received radiation. Exploding solutions with non-uniform density, pressure and radiation are in general very difficult to obtain in exact form. Considerable work therefore remains to be done. I have not discussed here the behaviour of material particles in detail. But it is clear from what has been said about photons that white holes can also pump out highly energetic particles such as those found in cosmic rays and like those required for producing strong radio emission. In the latter case anisotropically expanding white hole models may be needed.

CAN WHITE HOLES SURVIVE ?

This question has been raised by Eardley [15] and by Zeldovich et al. [16] under different contexts. The point raised by Zeldovich et al. relates to quantum particle creation in the early stages of the white hole history. Taking the specic case of an ever-expanding white hole they argue that fluctuations of the gravitational field in the beginning will create so much matter that the white hole will be swamped and will quickly turn into a black-hole. This particular objection appears to be model dependent and related to the particular hypothesis of particle creation. Since quantum particle creation in gravitational fields is not a well developed subject I would be inclined to reserve judgement on this particular objection.

The objection by Eardley refers to a white hole expanding in an empty space. He has argued that the white hole surface while crossing the horizon encounters a 'blueshift' surface. It therefore has a tendency to accrete ambient matter at ultra-relativistic speed; and this results in its quickly becoming a black-hole. This argument has recently been countered by Lake and Roeder [17] who have shown that for a white hole expanding as a delayed bang in a non-empty cosmological space-time the situation envisaged by Eardley does not arise. Lake and Roeder have argued that so long as time-like infinities which make null surfaces blue shift surfaces, are removed from the geometry of space-time, the ensuing white holes are stable with respect to blue shift horizons. I will not elaborate the argument further since it is of a rather technical nature.

CONCLUDING REMARKS

I have given instances of how white holes could play a major role in high energy astrophysics. It will be of interest to investigate the following questions further:

1. Are white holes stable? The stability has to be considered in many contexts two of which were outlined here.

2. Is it possible to have oscillating and/or non-singular models of white holes? These will be of interest to account for periodic bursters.

3. Could anisotropic white hole models, e.g., those with rotation or linear expansion be constructed? These will be applicable to strong radio sources.

4. Is it worthwhile looking for tachyons in exploding objects? The search for tachyons in laboratory has so far proved fruitless. White holes may be possible sites of such particles, if they exist.

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