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Highlights in Black Hole Astrophysics

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I review the theoretical and observational data supporting the existence of black holes at various mass scales and then give a brief account of the recent progress in the understanding of the stellar tidal disruption process, which is expected to play a prominent role in fuelling large black holes in galactic nuclei.

1. THEORETICAL VS. OBSERVATIONAL DATA FOR BLACK HOLES

1.1. The Theoretical Status of Black Holes

An elementary definition of a black hole is a region of spacetime in which the gravitational potential exceeds the square of the light speed. This is roughly equivalent to the condition that a given mass M must be confined within a critical surface (the event horizon) with typical radius GM/c^2. In order to achieve such a compactness, an astronomical body must undergo the process of complete gravitational collapse. The astrophysical status of black holes at various mass scales may be summarized in the mass-density diagram of Figure 1 [originally introduced by Carter (1973)]. The relationships between the mass M and the average density ρ of several kinds of celestial bodies are plotted in units of the solar values.

Black holes have obviously $\rho \propto M^{-2}$, and span a very wide mass spectrum, from primordial mini-black holes to supermassive ones.

In cold bodies, gravity is supported by quantum properties of matter (exclusion principle). Planets have roughly a constant density (i.e., independent of their mass), but cannot be more massive than the Fowler limit P. White dwarfs have $\rho \propto M^2$, but, supported by the pressure of degenerate electrons, they cannot be more massive than the Chandrasekhar limit C

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($1.4M_\odot$), above which the electrons become relativistic. Neutron stars are supported by degenerate neutrons and thus give rise to much higher density, up to the nuclear value. However, their mass cannot exceed the Landau limit *E*, above which the neutrons become relativistic and catastrophic gravitational collapse to a black hole must occur. The detailed value of the Landau mass limit M_L depends on the equation of state for nuclear matter; assuming general relativity and causality (speed of sound < speed of light), M_L should not exceed $3M_\odot$ [see Baym and Pethick (1979) for a review].

In hot bodies, gravity is supported by a central source of heat (for instance, thermonuclear reactions). Most of the stars are in the stage of hydrostatic equilibrium during which hydrogen burns peacefully into helium

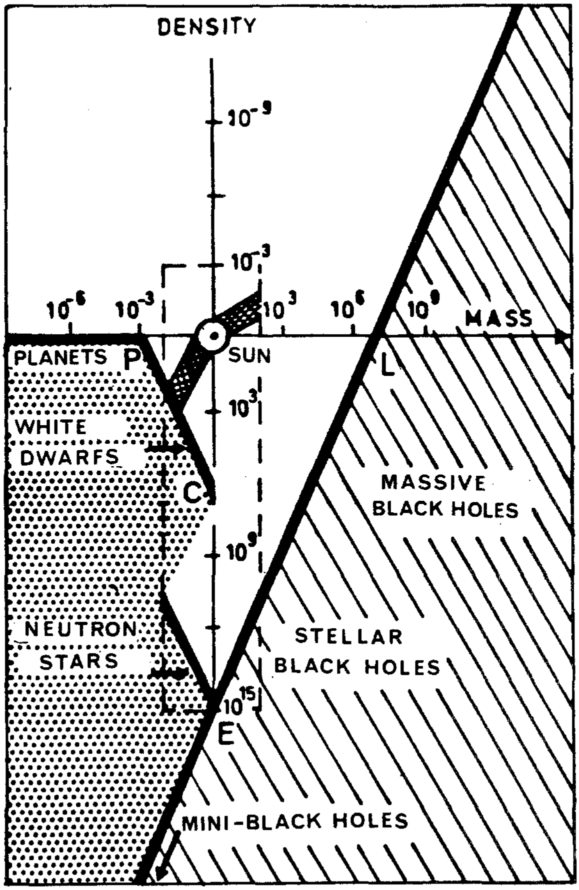

Fig. 1. The mass-density relationship for celestial bodies.

in their core. When the fuel is exhausted the stars leave the "main-sequence" track; their general motion in the mass-density diagram is directed toward the bottom (increasing density) and the left (decreasing mass).

1.2. The Formation of Stellar Black Holes

Figure 2 is an enlargement of the dashed rectangle of Figure 1 within which stellar evolution proceeds. White dwarfs, neutron stars, and stellar black holes are the possible endpoints of stellar evolution, the key parameter being the mass of the progenitor. Single stars less massive than $\sim 6M_\odot$ cease their nuclear evolution at or before the stage of core carbon burning and lead to white dwarf remnants. In stars with initial mass $> \sim 6M_\odot$, the core passes through all the exoergic burning phases until the building of the iron-group elements, and undergoes a supernova explosion which can be completely disruptive or leave behind a neutron star remnant or eventually a black hole for the most massive. Finally, the belief that black holes form by gravitational collapse of massive stars rests on the following statements:

1. Cold matter cannot support against gravity if the mass exceeds significantly the Landau limit $M_L \approx 3M_\odot$.
2. Many observed hot stars have $M \gg M_L$.
3. Such events must have already occurred, because the lifetime of massive stars prior to collapse is much less than the age of the galaxy.

The weak point of this argumentation lies in the fact that in supernova explosions, only the degenerate iron core undergoes gravitational collapse

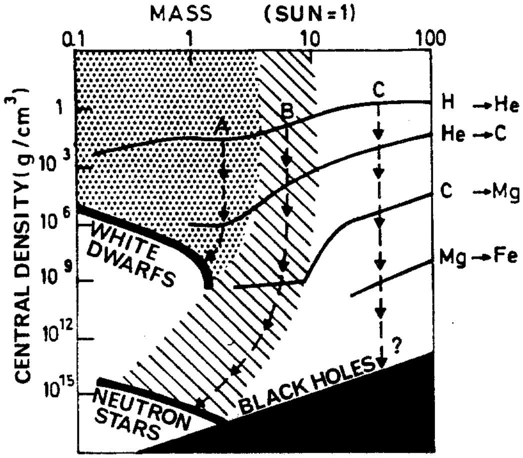

Fig. 2. The endpoints of stellar evolution.

and, whatever the total mass of the progenitor is, it is not clear whether the core can retain more than M_L; many poorly understood phenomena such as mass loss or convection could reduce systematically the core mass below M_L.

An experimental approach to the problem of gravitational collapse is numerical simulation. Although constrained by computer limitations, detailed calculations (see, for instance, Wilson, 1974) confirm that black holes form when the mass of the degenerate core exceeds M_L. If a neutron star forms first, it is also possible that subsequent accretion of the stellar envelope not expelled in the supernova explosion increases the mass above the Landau limit and a black hole would be formed by a "two-step" process. Such an exotic explanation has been invoked to account for the rather controversial neutrino detection at the Mont Blanc Laboratory from SN 1987*a*.

The formation of stellar black holes is also likely to take place in tight binary systems, where a supernova explosion gives birth to a neutron star. Then, on a much longer time scale, accretion of the gas of the companion star may increase the mass of the neutron star above the critical Landau limit, and again collapse to a black hole may occur.

By these various mechanisms there might be about 10^9 stellar black holes in our own galaxy.

1.3. The Formation of Mini-Black Holes

Mini-black holes could exist as relics of the earliest epochs of the big bang, when the universe was at supernuclear density (Hawking, 1971). The quantum evaporation process discovered by Hawking (1974) is significant only for holes less massive than 10^{15} g and size less than 1 fermi. Complete evaporation proceeds on a time scale of 10^{10} years $(M/10^{15}\text{ g})^3$. The temperature of evaporating mini-black holes increases above 10 MeV and most of the corresponding thermal radiation is in the gamma spectrum. Attributing the observed gamma-ray background to evaporating mini-black holes provides an upper limit to their number density, which must be extremely low (less than 10^{-8} times the critical density). If there are some theoretical and aesthetic reasons supporting the idea of primordial mini-black holes, we are forced to admit that there is not a piece of observational data.

1.4. The Formation of Massive Black Holes

Three basic possibilities exist:

1. The maximum mass of primordial black holes at a given time is determined by the mass of the horizon. Thus, giant black holes with $M > 10^5 M_\odot$ may have formed slightly after the nucleosynthesis time

($t \approx 100$ sec). However, unless those black holes are now hidden in the nuclei of galaxies, the existence of significant quantities of isolated massive black holes is ruled out by the absence of gravitational lensing and distortion of the microwave background.

2. Due to the very short lifetime of massive stars, a $10M_\odot$ black hole could have formed very early in the nuclear regions of a galaxy. If sufficiently fed in gas, such a "seed" black hole may grow (at the Eddington rate) to a supermassive black hole in less than a Hubble time (Hills, 1975).
3. Dense stellar clusters are expected to undergo gravitational collapse leading directly to a massive black hole (Zel'dovich and Podurets, 1965). Numerical simulations (Shapiro and Teukolsky, 1985) describe the fate of a "relativistic stellar cluster;" they start with a cluster of neutron stars and stellar black holes and compute the evolution. The collapse of the core to a massive black hole occurs in less than a Hubble time if the initial cluster parameters lie in the range $N_c = 10^7\text{–}10^8\ \mathrm{pc}^{-3}$, $v_c = 1000\text{–}2000$ km/sec (plausible values for galactic nuclei).

1.5. The Observational Status of Black Holes

A newborn black hole signals its formation by a burst of gravitational waves, but the prospects for such a detection are still remote. The present challenge of astronomers is to detect black holes indirectly, through the electromagnetic radiation emitted by gas and stars interacting with them.

1.5.1. Black Holes in binary Systems

The procedure here is to look at binary X-ray sources which are neither periodic nor recurrent (otherwise they should be interpreted as containing neutron stars). Select rapidly flickering sources: fluctuations of luminosity on a time scale of 10^{-4} sec indicate a typical size of 30 km for the emitting region. This is, however, an ambiguous criterion for a black hole, since some X-ray sources which exhibit such rapid fluctuations harbor a neutron star. In fact, the only way to test properly the black hole hypothesis is to weigh the stars.

This can be done from the optical measurement of the mass function $f(M)$, derived from the orbital period P and the projected orbital velocity of the primary $v^* \sin i$:

$$f(M) = \frac{(M_x \sin i)^3}{(M_x + M_*)^2} = \frac{P^2 (v^* \sin i)^3}{2\pi G}$$

where the indices x and $*$ label, respectively, the compact and the primary star. Additional information is inferred from (1) the optical luminosity and the spectral type of the primary, which gives an order of magnitude of M_*, and (2) the presence or absence of X-ray eclipses, which provides bounds to the inclination angle i. Then from the mass function one deduces $M_{\min} < M_x < M_{\max}$. Black hole candidates are retained only if $M_{\min} > 3M_\odot$. At present (1988), three binary X-ray sources unambiguously satisfy the test: Cygnus X-1, LMC X-3, and A0620-00.

In the Cygnus X-1 system (Gies and Bolton, 1986), the primary is a blue giant star whose mass lies in the range $20M_\odot < M_* < 40M_\odot$. The orbital period is 5.6 days and the inclination angle must exceed 55°. One deduces $7M_\odot < M_x < 20M_\odot$. A more stringent lower limit for M_x may be obtained, based on the absence of eclipses and dependent only on the distance of the source. If $d = 2$ kpc, it gives $3.4M_\odot$ (whatever M^* is), but this lower mass limit drops slightly below the critical threshold $3M_\odot$ if d is reduced by a few percent; then the case becomes inconclusive.

The LMC X-3 system (Cowley *et al.*, 1983) is extragalactic (it belongs to the Large Magellanic Cloud, at 170,000 light years). The primary is a blue star with $4M_\odot < M_* < 8M_\odot$ and the compact star should have $7M_\odot < M_x < 14M_\odot$.

The A0620-00 system (McClintock and Remillard, 1986) is remarkable by the fact that it is a low-mass binary system: the primary is a dwarf star with $0.5M_\odot < M_* < 0.8M_\odot$ and the compact star should have $M_x > 3.2M_\odot$. It may be the cleanest stellar black hole candidate; it is also the most ancient observed one, since it appeared on a photographic plate in 1917 during an optical burst (it was then interpreted as a nova).

With three such excellent black hole candiates, *ad hoc* models, invoking, for instance, a third star in the system, are very unlikely (the binary A0620-00 is in fact so tiny that a third body would have no place to stand!); there is little doubt that in the near future new black hole candidates will arise after detailed measurements of half a dozen promising X-ray binaries.

1.5.2. Large Black Holes in Galactic Nuclei

Giant black holes were long ago proposed by theoretical astrophysicists (Zel'dovich, 1964; Lynden-Bell, 1969) as plausible powerhouses of active galactic nuclei. Paradoxically, the best observational support for the massive black hole hypothesis comes from galaxies which are far from being active. Mass concentrations in galactic nuclei can be inferred from (1) the distribution of light near the center (a spike in the luminosity profile signals a central pit) and (2) dynamical arguments. Spectroscopic measurements give the velocity dispersion of stars or emitting clouds surrounding the black hole candidate. Assuming that the mass distribution is spherical, the mean rotation is circular, and the stellar motions are isotropic, the total mass within radius r is deduced from the Blasov equation as

$$M(r) = \frac{rv^2}{G} - \frac{r^2}{\rho G}\frac{d}{dr}(\rho\sigma^2) \tag{1}$$

where ρ is the stellar number density, v the rotation velocity, σ the radial component of the velocity dispersion, and G the gravitational constant.

The Galactic Center in Sagittarius is the nearest massive black hole candidate (Crawford *et al.*, 1985; Lo, 1986). Its bolometric luminosity is $10^7 L_\odot$ emitted from a region smaller than 30 light years. In the radio band, two compact radio sources are detected: Sag A East is probably a supernova remnant, whereas Sag A West exhibits a thermal component due to the emission of a cloud and a nonthermal component due to synchrotron radiation. This last source, called Sag A W*, is powerful and compact (less than 20 A.U.). Various astrophysical objects can emit radio waves—for instance, pulsars and young supernova remnants. Sag A W* cannot be a pulsar because its radio luminosity is much too high (by 10^4) and is not pulsating; it cannot be a supernova remnant because its expansion velocity is too low (less than 15 km/sec). In fact, Sag A West* is probably not an object of stellar mass; otherwise, it would have a typical dispersion velocity of ~150 km/sec; this is far from being the case, since Sag A West* is practically at rest. The radio data are thus consistent with a $10^6 M_\odot$ black hole in a slow accretion state.

The infrared source IRS 16 coincides nearly with Sag A West*. If the emission is interpreted in terms of red giant stars, the IR intensity traces the number density of stars: $2 \times 10^6 M_\odot$ must gravitate within 5 light years. This is a very high density indeed, compared to the centers of globular clusters. Infrared emission is also due to clouds at 300 K. Spectroscopic measurements provide the velocity of the clouds, then the total mass of IRS 16 from (1). The dynamical mass thus obtained is $5 \times 10^6 M_\odot < M < 8 \times 10^6 M_\odot$. Subtracting the mass of red giants, the remaining unseen mass is $3 \times 10^6 M_\odot < M < 6 \times 10^6 M_\odot$.

The debate is not yet closed, since one can argue that the assumptions of (1) are not satisfied. The motion of clouds might also not be gravitational (due, for instance, to acceleration by radiation pressure). In such a case, the unseen mass should drop to a few hundreds $M_\odot$.

The giant elliptical Messier 87 has been thoroughly studied. Photometry of the central region together with measurements of the stellar velocity dispersion suggest the presence of a central dark mass of $3 \times 10^9 M_\odot$ (Young *et al.*, 1978; Sargent *et al.*, 1978). However, anisotropy could spoil the conclusion (Binney and Mamon, 1982) and the choice between a supermassive black hole and a right stellar cluster is still open [see Dejonghe (1988) for a review].

Similar kinematic phenomena have been found in nearby galactic nuclei, such as the Andromeda Galaxy M31 (Kormendy, 1988; Dressler and Richstone, 1988), the dwarf elliptical Messier 32 (Tonry, 1984) or the Sombrero galaxy M104 (Jarvis and Dubath, 1988), requiring the presence of $(10^6\text{-}10^8)M_\odot$ concentrations, plausibly giant black holes.

Active galactic nuclei such as Seyfert galaxies, BL Lac objects, quasars, and radiosources should harbor still more massive central condensations. Black holes are generally suspected to be the prime movers, but their presence is inferred from very indirect arguments (the short-time-scale variability signals the compactness of the source, the Eddington Luminosity and energetic considerations provide orders of magnitude for the mass).

The alternative black hole models in galactic nuclei (e.g., dense stellar clusters, supermassive stars) are much more disputable both from a theoretical basis and from an observational point of view [see Luminet (1988*a*) for a review]. The accreting massive black hole is thus at present the "conventional" explanation of the activity of galactic nuclei.

To conclude this part, I note that the observational status of stellar and massive black holes has gained the same level of controversy as the interpretation of redshifts of QSO in terms of cosmic expansion: extremely low.

2. THE TIDAL SIGNATURE OF BIG BLACK HOLES

Fuelling a massive black hole in an active galactic nucleus whose luminosity can be as high as 10^{46} ergs/sec requires the digestion of $1 M_\odot$ per year. Various mechanisms are likely to release large amounts of gas, such as the ablation of stellar atmospheres by the external radiation field and the more or less violet disruption of stars by tidal stresses or by high-velocity interstellar head-on collisions (expected to be predominant in the vicinity of $> 10^9 M_\odot$ black holes, for which the tidal disruption process becomes inefficient).

Carter and Luminet (1982, 1983) made the first prediction that the external tidal field generated by a large black hole can act on a star deeply plunging into its tidal radius as a detonator of explosive nucleosynthesis. They proved that in the more extreme form of tidal stellar disruption, the stellar core, instead of being continuously decompressed and broken into filamentary clouds, first undergoes a transitory phase of huge compressional flattening and heating, whose effects on the dynamics and the chemical composition of the released gas may be of primary importance (Luminet, 1988*b*). This phenomenon can be easily understood by recalling that inside the tidal radius, the external gravitational forces dominate rapidly the internal pressure and self-gravitational forces, so that the particles of the star undergo free-fall motion; then, since the direction orthogonal to the orbital plane is a fixed, compressive eigendirection of the tidal tensor, particles of the star will have a tendency to cross the orbital plane. Of course, when the volume of the star tends to zero the internal pressure will suddenly react to prevent the caustics and the star will bounce to a phase of expansion and ejection of its gas. It is thus clear that the star must pass through a fixed point near the periastron of its orbit, at which it will look like a squeezed tube of toothpaste. This squeezing effect may be viewed as a "pancake" effect in the sense that it can be considered as simultaneous all over the star due to the very large orbital velocity compared to the internal sound speed.

The amplitude of flattening depends on the penetration factor β, defined as the ratio of the tidal radius to the pericentric distance. As an example, a solar-type star plunging by a factor 15 inside the tidal radius of a $10^5 M_\odot$ black hole (i.e., along a parabolic orbit with pericentric distance 9.1×10^5 km) is compressed by a factor of $\sim$750 and heated by a factor of $\sim$80 during $\sim$0.1 sec (Luminet and Carter, 1986). An interesting relativistic effect in the Schwarzschild gravitational field of a nonrotating black hole is that, when the parabolic orbit of the star has a double point inside the tidal radius, the star passes through several squeezing points and suffers successive pancake flattenings separated by a few seconds (Luminet and Marck, 1985).

To study in more detail the dynamics of violent disruption, it is convenient to use in a first approximation an affine star model (Carter and Luminet, 1985) which allows compressibility, inhomogeneity, entropy generation by nuclear processes or viscosity, and so on, but in which the layers of constant density are constrained to keep an ellipsoidal form. Such a solution is an exact one in the incompressible limit, and is likely to provide a good description of the behavior of the main bulk of a realistic star, at least until the phase of bounce occurs (after which shock waves and significant nonlinearities will develop). In the most recent calculations, Luminet and Pichon (1988*a*,*b*) examined the cases of main-sequence stars orbiting $(10^5\text{–}10^6)M_\odot$ black holes and of degenerate stars (white dwarfs, helium stars) grazing $10^3 M_\odot$ black holes. They considered a nonadiabatic affine star model moving in a Schwarzschild tidal field along a nearly parabolic orbit. The equation of state of the stellar material is a mixture of a nonrelativistic perfect ion gas, a semidegenerate semirelativistic electron gas, and a photon gas. Typically, the central temperature is increased by a factor of $\sim$50 and the density by a factor of $\sim$100 within a few milliseconds with $\beta\sim15$ in a main-sequence star, or with $\beta\approx5$ in a degenerate dwarf

Table I

	Initial composition	Final composition	Nuclear energy release
$1M_{\odot}$ Main-sequence star	64% ^{1}H, 33% ^{4}He 2% ^{14}N, 1% ^{16}O	($\beta = 15$) 63.6% ^{1}H, 33.1% ^{4}He, 0.2% ^{14}N, 2.5% ^{15}N, 0.2% ^{25}Mg, 0.2% ^{26}Ag 0.2% ^{26}Mg, 0.2% ^{27}Al	16.1×10^{49} ergs
$0.6M_{\odot}$ Degenerate star	40% ^{4}He, 25% ^{12}C, 25% ^{16}O, 5% ^{20}Ne, 5% ^{24}Mg	($\beta = 4$) 2.2% ^{4}He, 68.1% ^{12}C 19.2% ^{16}O, 8.5% ^{28}Si, 0.9% ^{32}S	6.1×10^{49} ergs

star. In such thermodynamic conditions, neutron-producing reactions are negligible and the main nuclear flow is dominated by alpha-capture or proton-capture reactions. Therefore they calculate the nucleosynthesis using a nuclear network including (1) 42 isotopes comprised between the valley of stability and the proton drip line, liked by 44 strong reactions and 24 weak decays in the case of main-sequence stars, and (2) "multiple-of-alpha" isotopes ranging from ^{4}He to ^{56}Ni in the case of degenerate dwarf stars.

They considered also the coupling between the affine hydrodynamics and the nuclear network via an entropy equation which takes account of the nuclear power output as well as of the changes in chemical composition. The calculations confirm that the tidal squeezing with sufficiently high β may trigger explosive nucleosynthesis in the stellar core and release more nuclear energy than the gravitational binding energy, as shown in Table I.

In main-sequence stars, about 50% of the stellar debris escapes the black hole and is diluted into the interstellar medium, injecting the specific isotopes of Table I. In helium dengenerate stars, helium flash may occur, but the gas remains bound to the black hole.

The production of heavy isotopes in stellar pancakes as well as the dynamics of ejected gas constitute real signatures of the existence of large black holes in the core of galaxies, and such effects should be soon detectable by means of advanced spectroscopic techniques.

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