9.8: Black Hole

over the edge with a scream of radiation

A black hole is a domain whose mass is so tightly compacted that nothing can escape from it, not even light. Everything that falls in is caught without hope of escape (Figure $9.8.1$).

'Escape velocity c" implies black hole

To fire a missile from Moon's surface so that it escapes that satellite's attraction demands a speed of 2.38 kilometers per second or greater. The critical speed for escape from Earth - in the absence of drag from the atmosphere - is 11.2 kilometers per second. When the object does not rotate and is so compact that even light cannot escape, the "effective radius" or so-called "horizon radius" is

$$\begin{aligned}(\text{effective radius}) &= \frac{\begin{pmatrix}\text{circumference of region}\\ \text{out of which}\\ \text{light cannot escape}\end{pmatrix}}{2\pi} \\ &= 2 \times (1.47 \text{ kilometers }) \times \begin{pmatrix}\text{mass of black hole}\\ \text{expressed in}\\ \text{number of Sun masses}\end{pmatrix}\end{aligned}$$

Black hole still exerts " pull" of gravity

When a star or cloud of matter collapses to a black hole it disappears from view as totally as the Cheshire cat did in Alice in Wonderland. The cat, however, left its grin behind; and the black hole-via the effect of spacetime curvature that we call gravity - exerts as much "pull" as ever on normal stars in orbit around it. They are like participants in a formal dance with lights turned low. Only the white dress of the girl is visible as she whirls around in the arms of her black-suited companion. From the speed of the girl and the size of the circle in which she swirls, we know something of the mass of the invisible companion. By such reasoning it was possible to conclude by 1972 that the optically invisible companion of one long-known star has a mass of the order of 9.5 solar masses.

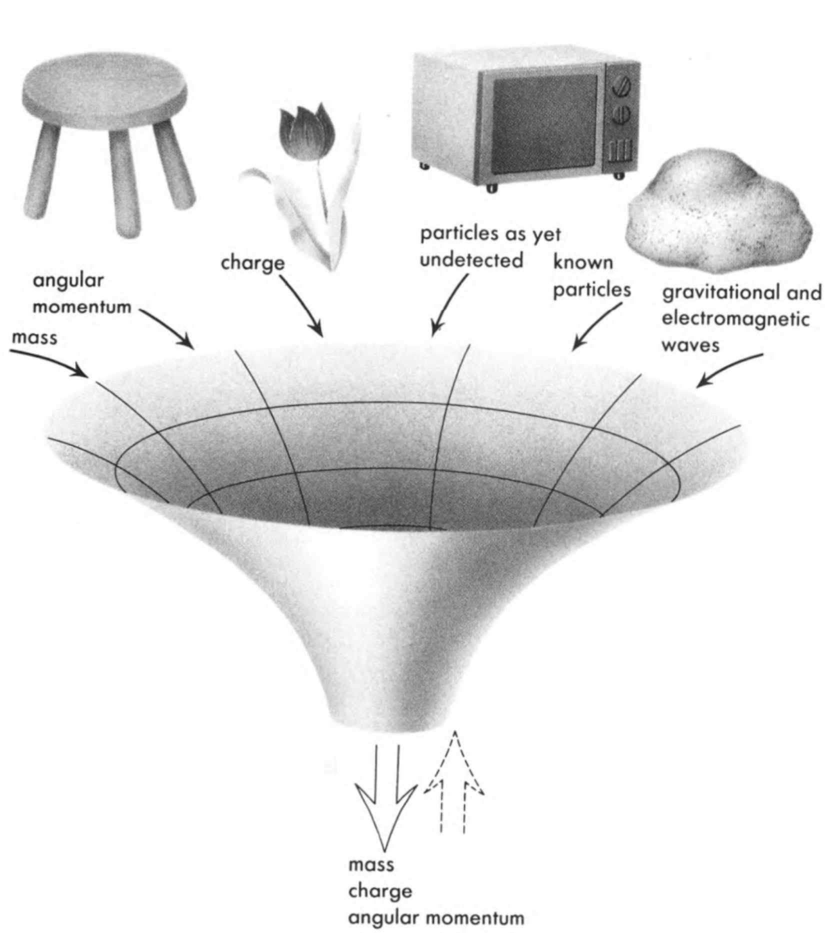

Figure 9.8.1: Whatever objects fall into a black bole, they possess at the end-as seen from outside -only mass, angular momentum, and electric charge. Not one other characteristic of any in-falling object remains to betray its past - not a hair. This leads to the saying, "A black hole bas no hair."

Cygnus X-1: A black hole?

This remarkable object came first to attention because in December 1971 the Uhuru orbiting X-ray observatory detected X-ray pulsations with time scales from one tenth to tens of seconds from an object located in the Cygnus region close to the known star. Why does it give off X-rays? And why does the intensity of the X-rays vary rapidly from instant to instant? The gas wind from the visible companion varies from instant to instant like the smoke from a factory chimney. This gas, falling on a compact object, gets squeezed. To picture the how and why of this squeeze, look from a low-flying plane at the streams of automobiles converging from many directions on a football stadium for a Saturday afternoon game. The particles and the gas are pushed together as surely as the cars in the traffic. The compression of the traffic raises the temper of the driver, and the compression of the gas raises its temperature as air is heated when pumped in a bicycle pump. However, because the gas falls from an object of millions of kilometers in size to one a few kilometers across, the compression is so stupendous that the temperature rises far above any normal star temperature, and X-rays come off.

The time scale of the fluctuations in X-ray intensity depends on the size of the object that is picking up the star smoke, a size less by a fantastic factor than that of any normal star. Could the object be a white dwarf (Box 9-2)? No, because such a star would be visible. A neutron star? No, because even matter compressed so tightly that it is transformed to neutrons cannot support itself against gravity if it has a mass much over two solar masses. No escape has been found from concluding that Cygnus $\mathrm{X}-1$ is a black hole. This great discovery transformed black holes from pencil-and-paper objects into a lively and ever-growing part of modern astrophysics (Table 9.8.1).

Table 9.8.1: BLACK HOLES FOR WHICH THERE WAS SUBSTANTIAL EVIDENCE AS OF SEPTEMBER 1989 (Uncertainties in masses are of the order of 20 to 50 percent.)

Astronomical designation of black hole	Mass (in solar masses
Cygnus X-1	9.5
LMC X-1	2.6
AO 620-00	3.2
LMC X-3	7.0
SS 433	4.3
Black hole at center of our galaxy	3.5×10^{6}

Black hole at center of our galaxy?

Much attention went in the 1980 s to a presumptive black hole with a mass of about three and a half million times the solar mass and a horizon radius of about ten million kilometers. It floats at the center of our galaxy, the Milky Way. Around it buzz visible stars of the everyday kind, most of them fated to fall eventually into that black hole and increase its mass and size. That stars close to the center of our galaxy go around as fast as they do is one of the best indicators we have for the presence, and one of the best measures we have for the mass, of the central black hole, which is itself invisible.

Quasar energy output from matter swirling into black hole?

In contrast to dead solitary black holes, the most powerful source of energy we know or conceive or see in all the universe is a black hole of many millions of solar masses, gulping down enormous amounts of matter swirling around it. Maarten Schmidt, working at the Mount Palomar Observatory in 1956 , was the first to uncover evidence for these quasistellar objects, or quasars, starlike sources of light located not billions of kilometers but billions of light-years away. Despite being far smaller than any galaxy, the typical quasar manages to put out more than a hundred times as much energy as our own Milky Way, with its hundred billion stars. Quasars, unsurpassed in brilliance and remoteness, we call lighthouses of the heavens

High-efficiency conversion of gravitational energy to radiation

Observation and theory have come together to explain in broad outline how a quasar operates. A black hole of some hundreds of millions of solar masses, itself built by accretion, accretes more mass from its surroundings. The incoming gas, and stars-converted-to-gas, does not fall in directly, any more than the water rushes directly down the bathtub drain when the plug is pulled. Which way the gas swirls is a matter of chance or past history or both, but it does swirl. This gas, as it goes round and round, slowly makes its way inward to regions of ever-stronger gravity. Thus compressed, and by this compression heated, the gas breaks up into electrons - that is negative ions - and positive ions, linked by magnetic fields of force into a gigantic accretion disk. Matter little by little makes its way to the inner boundary of this accretion disk and then, in a great swoop, falls into the black hole, on its way crossing the horizon, the surface of no return. During that last swoop, hold on the particle is relinquished. Therefore, the chance is lost to extract as energy the full 100 percent of the mass of each infalling bit of matter. However, magnetic fields do hold onto the ions effectively enough for long enough to extract, as energy, several percent of the mass.

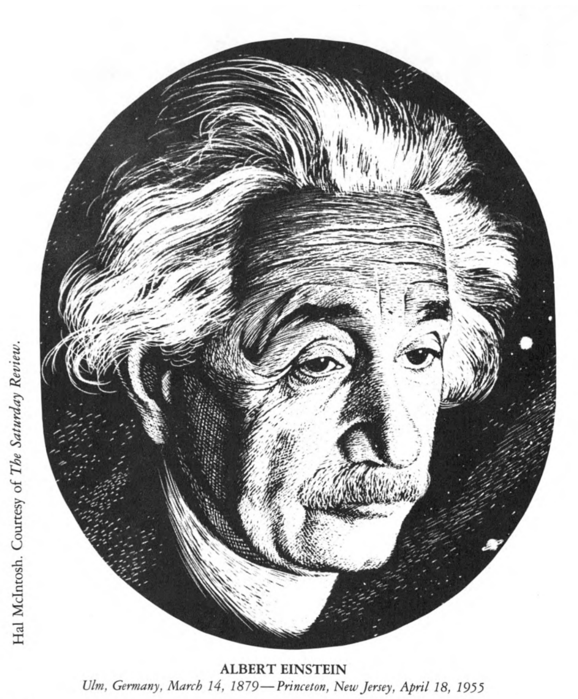

Figure 9.8.2

> *"Newton himself was better aware of the weaknesses inherent in his intellectual edifice than the generations which followed him. This fact has always roused my admiration."*

> *"Only the genius of Riemann, solitary and uncomprehended, had already won its way by the middle of the last century to a new conception of space, in which space was deprived of its rigidity, and in which its power to take part in physical events was recognized as possible."*

> *"All of these endeavors are based on the belief that existence should have a completely harmonious structure. Today we have less ground than ever before for allowing ourselves to be forced away from this wonderful belief."*

In contrast, neither nuclear fission nor nuclear fusion is able to obtain a conversion efficiency of more than a fraction of a percent. Of all methods to convert bulk matter into energy, no one has ever seen evidence for a more effective process than accretion into a black hole, and no one has even been able to come up with a more feasible scheme for one.

Of all the features of black hole physics in action, none is more spectacular than a quasar. And no lighthouse of the skies gives more dramatic evidence of the scale of the universe.

Three quotations under the Einstein picture come from Albert Einstein, Essays in Science (Philosophical Library, New York, 1934).

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