PERSPECTIVES: ASTRONOMY

The Buzz of General Relativity

Michiel van der Klis

In Einstein's general theory of relativity, gravity is described as a curvature of the four-dimensional space-time continuum in which we live. Observations by NASA's Rossi X-ray Timing Explorer (RXTE) (*1*) are now providing the first direct measurements of the orbital motion of matter in strongly curved space-times, where the laws of motion are predicted to be qualitatively different from those in the Newtonian mechanics that dominate our solar system and most other systems we know.

In Einstein's theory, when gravity is weak and hence space-time curvature is small, the motion of matter is nearly, but not exactly, that predicted by Newton's laws. Such small deviations have been confirmed by studies of millisecond radiopulsars (*2*). However, no direct measurements have ever been performed to measure the gross deviations from Newtonian mechanics predicted in strongly curved space-time: Relativity has not been tested in this "strong-field" regime.

The strongest space-time curvatures that are accessible to observations are those near collapsed massive stars. These objects concentrate within a few kilometers the mass of a star one to several times the mass of the sun (one solar mass is 2×10^{30} kg). They have the strongest gravity, and hence curve space-time the tightest, of all known objects in the universe. Some are so massive that they can only be black holes. The radius of a black hole in kilometers is about three times its mass in solar masses. By a freak of nature, there is a small range of masses, ranging from 1.4 to somewhere between 2 and 3.5 solar masses, in which a collapsing star forms an object that is slightly larger than a black hole of the same mass would be: a neutron star. The pressure in such a star is so high that the electrons and protons of ordinary matter merge and the star consists mostly of neutrons. It has a density exceeding that of an atomic nucleus and a radius of between 7 and 15 km. The uncertainties in radius and upper mass limit (above which the neutron star collapses into a black hole) reflect our basic lack of knowledge of the compressibility of neutron matter: The equation of state, describing this compressibility of matter, is uncertain at the "supranuclear" densities inside a neutron star. Thus, measuring the motion of matter in close orbit around neutron stars and black holes tells us about the fundamental properties of space-time, and measuring masses and radii of neutron stars tells us about the fundamental properties of matter.

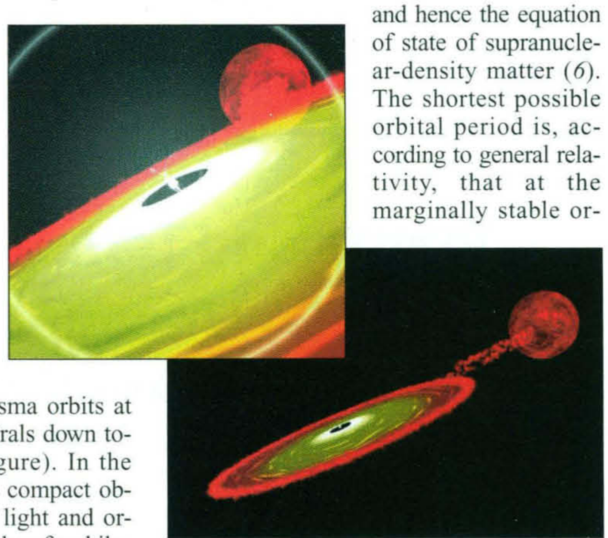
The author is at the Astronomical Institute "Anton Pannekoek," University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, Netherlands. E-mail: michiel@astro.uva.nl

The discovery, in the early 1960s, of x-ray binaries, double stars where a compact object—a neutron star or a black hole—orbits a normal star and pulls a flow of plasma out of the star's atmosphere onto itself (see the figure), has long held the promise of providing a natural laboratory for studying orbital motion in strongly curved space-time. Since the launch of the Rossi Explorer 3 years ago, these systems have finally begun to make good on that promise. The process of "accretion," by which matter flows from the normal star onto the neutron star or into the black hole, produces a differentially rotating disk around the compact object, in which the plasma orbits at ever increasing speed as it spirals down toward the center (see the figure). In the strong gravity region near the compact object, speeds approach that of light and orbital radii of the plasma are only a few kilometers, such that the orbit of a particle around the center takes less than a millisecond to complete.

Before Rossi, such short periods were not seen in x-ray binaries. RXTE, the largest area x-ray instrument ever pointed at an x-ray star, was specifically designed to look for them. One might have expected to see a broad spectrum of fluctuations in the x-rays with periods corresponding to the orbital periods at different radii in the accretion disk. Instead, two distinct millisecond periods were observed (*3*). These signals are only "quasi" periodic and if made audible would sound more like a buzz than a pure tone, yet they are so well defined that the motion causing them must repeat without change for hundreds of cycles. Such coherence immediately suggests orbital motion at at least one specific radius (a second period can be generated from the first one in another way, see below). The fastest signals, seen in neutron stars, have periods as short as 0.75 milliseconds, corresponding to orbital motion at a 12-km radius, deep within the strong-field gravity region and perilously close to the so-called "marginally stable" orbital radius within which Einstein, in qualitative departure from Newton, predicts that no stable orbits are possible. Apparently, matter is able to stay in orbit for tens of milliseconds before finally plunging down.

These phenomena have now been seen in some 20 neutron stars (*4*). Three black holes have also shown periods down to as short as 3 milliseconds, which given their higher masses imply that the signals come from a similar depth in the strong gravity region around them as in the neutron stars (*5*).

How can this relativist's dream, the direct observation of the periods of orbital motion in strong-field gravity, be put to best use? An orbital period around a neutron star as short as 0.75 milliseconds severely constrains the mass and the radius that the star can have and hence the equation of state of supranuclear-density matter (*6*). The shortest possible orbital period is, according to general relativity, that at the marginally stable orbital radius. The observed orbits are apparently very close to this radius, and it may thus be possible to detect its existence in the form of a lower cutoff in the observed periods (*7*). Several claims of the detection of such a cutoff have already been made (*8*). If correct, this would be the first direct evidence for a strong-field general-relativistic effect. The neutron star masses in these systems, which can be deduced directly from the cutoff frequencies, would then be quite high, more than two solar masses, suggesting that most proposed equations of state—according to which stars of such mass would have already collapsed into black holes—are too soft. However, whether the cutoff is real is still the subject of lively debate.



Unequal partners. (Bottom) Artist's impression of small, gravitationally deformed red star feeding matter to the flat accretion disk within which matter swirls down toward a compact object. **(Top)** Detail showing the inner edge of the disk and the final plunge of the matter down onto the compact object (in this case, a slightly magnetic neutron star).

Detailed modeling of the new phenomena is under way. Two teams have championed the view that we are directly seeing the "epicyclic" periods general relativity predicts for the orbital motion of test particles: one related to the well-known general-relativistic precession of Mercury's orbit (but 10^{17} times faster because of the strong gravity) and another to the so-called "Lense-Thirring precession" of the orbital plane itself, caused by "frame-dragging," a phenomenon in which a spinning object drags space-time around it along with its spin (*9*). But there seems to be more to it than that. RXTE has discovered the first millisecond pulsar in an x-ray binary, a neutron star spinning with a 2.493919753-ms period (*10*), and has measured the approximate spins of another six neutron stars with periods of 2 to 4 ms (*11*). Comparison of these spins with the millisecond quasi-periods suggests that while the fastest of the two quasi-periods seen in each system originates in the orbital motion in the accretion disk, the slower one (still sometimes as fast as 1.2 msec) arises by a nonlinear interaction (a "beat") between the spin and the orbital motion. One model describes a pattern of orbital motion that could explain the observations in detail (*7*). A few more years of observations, more discoveries, and further high-precision measurements of the new phenomena will show which of these theories can be maintained and which must be abandoned.

RXTE's success has demonstrated that when probing the dynamics in strongly curved space-time, there is no substitute for size. It is the huge effective area of 0.7 m^2 of the main x-ray instrument onboard the satellite that gave Rossi the sensitivity to make the first direct measurements of orbital motion near collapsed stars. To fully exploit these discoveries and map out space-time near neutron stars and black holes, an instrument in the 10-m^2 class will be required. Although the stream of new data from RXTE continues unabated and a second millisecond timing mission (the Naval Research Laboratory's Unconventional Stellar Aspect experiment on the Argos satellite) was just launched successfully, x-ray astronomers are already considering the new solid-state technologies by which such a "relativity explorer" might be realized.

References and Notes

1. H. V. Bradt, R. E. Rothschild, J. H. Swank, *Astron. Astrophys.* **97**, 355 (1993).
2. J. H. Taylor and J. M. Weisberg, *Astrophys. J.* **345**, 434 (1989).
3. M. van der Klis *et al.*, *ibid.* **469**, L1 (1996); T. E. Strohmayer *et al.*, *ibid.*, p. L9.
4. M. van der Klis, preprint available at xxx.lanl.gov/abs/astro-ph/9812395.
5. E. H. Morgan *et al.*, *Astrophys. J.* **482**, 993 (1997); R. A. Remillard *et al.*, *ibid.* **517**, L127 (1999).
6. W. Kluzniak *et al.*, *ibid.* **358**, 538 (1990).
7. M. C. Miller *et al.*, *ibid.* **508**, 791 (1998).
8. P. Kaaret *et al.*, *ibid.* **480**, L27 (1997); W. Zhang *et al.*, *ibid.* **482**, L167 (1997); W. Zhang *et al.*, *ibid.* **500**, L171 (1998); P. Kaaret *et al. ibid.* **520**, L37 (1999).
9. L. Stella, M. Vietri, W. Cui, *ibid.* **492**, L59 (1998); W. Cui *et al.*, *ibid.*, p. L53; L. Stella and M. Vietri, *Phys. Rev. Lett.* **82**, 17 (1999).
10. R. Wijnands and M. van der Klis, *Nature* **394**, 344 (1998); D. Chakarbarty and E. H. Morgan, *ibid.*, p. 346.
11. T. E. Strohmayer *et al.*, *Nucl. Phys. B* **69**, 129 (1998).

12. M. v. d. K. gratefully acknowledges hospitality at the Aspen Center for Physics.

PERSPECTIVES: PALEOECOLOGY

Plants and Temperature-CO_2 Uncoupling

Sharon A. Cowling

Measurements of CO_2 and oxygen isotopes in polar ice caps indicate that for at least the past 420,000 years, temperature and CO_2 trends have been coupled; cooling generally coincides with low CO_2 and warming with higher CO_2 (*1*). This observation may lead us to believe that changes in CO_2 and temperature have been coupled throughout Earth's history and will continue to be coupled in the future. However, recent estimates (*2–4*) of CO_2 concentrations of 180 to 240 µmol mol^{-1} for the mid-Cenozoic [between 17 and 43 million years ago (Ma)] are well below modern CO_2 concentration of 360 µmol mol^{-1}, at a time when at least some regions are thought to have been up to 6°C warmer than today (*5*). Degassing of biogenic methane hydrates may have been responsible for abrupt mid-Cenozoic warming (*6*); however, increases in other greenhouse gases such as water may have also caused temperatures to rise without concurrent increases in atmospheric CO_2. Such temperature-CO_2 uncoupling, if confirmed by further studies, may influence our ideas about climate-forcing mechanisms (*5*) and paleoecosystem form and function.

The author is in the Climate Impacts Group, Institute of Ecology, Lund University, S-223 62 Lund, Sweden. E-mail: Sharon.Cowling@planteco.lu.se

Temperature-CO_2 uncoupling is predicted to have strong effects on the fundamental process of carbon fixation in most plants. There are two major classes of plants defined by their carbon fixation pathway—C_3 and C_4. The primary enzyme for carbon fixation in C_3 plants—mostly tropical grasses—is ribulose-1,5-bisphosphate (or Rubisco). Rubisco fixes O_2 in competition with CO_2 in a process called photorespiration, which results in a loss of fixed carbon and reduced efficiency of C_3 photosynthesis. Reductions in atmospheric CO_2 and rises in temperature independently increase photorespiration (*7*). In a scenario where climate-CO_2 trends are uncoupled so that climate warming is not accompanied by increases in atmospheric CO_2, C_3 photosynthesis may be extremely low because of high rates of photorespiration. In contrast, because the primary carboxylating enzyme in C_4 plants does not react with O_2, C_4 plants can out-compete C_3 in low CO_2 and high temperature environments (*8*).

Our present understanding of how C_3 plants respond to changes in temperature and CO_2 can be used to constrain low-end CO_2 estimates made from geological data, particularly for the Cenozoic before 15 Ma, when terrestial ecosystems predominantly contained plants with the C_3 photosynthetic pathway. Because the paleorecord indicates that land plants survived and thrived throughout the Cenozoic, any geologically predicted CO_2-

TEMPERATURE–CO_2 INTERACTIONS AND PLANT CARBON

Experiment	CO_2 (µmol/mol)	Temperature (°C)	Photorespiration* (percent)	Net photosynthesis (µmol/m^2s)
Modern	360	25	11	17
control	360	32	18	11
LGM†	200	25 – 5	15	10
	200	32 – 5	24	8
Miocene‡	260	25 + 2	18	11
	260	25 + 5	22	9
	260	32 + 2	29	6
	260	32 + 5	35	4
	220	25 + 2	21	9
	220	25 + 5	26	7
	220	32 + 2	34	4
	220	32 + 5	41	3
Eocene§	385	25 + 2	12	16
	385	25 + 5	15	14
	385	25 + 2	19	10
	385	32 + 5	24	7
	180	25 + 2	26	7
	180	25 + 5	32	5
	180	32 + 2	41	3
	180	32 + 5	50	1

*Percent of gross photosynthesis. †Last Glacial Maximum (LGM, 21,000 years ago). ‡Miocene CO_2 limits from (*2*). §Eocene CO_2 limits from (*3*).