which took place over the Eastern United States in June 1976.

The effect being verified is caused by the action of gravity on time, which forces clocks (and all natural activity) to run more slowly in the Earth's gravitational field. At high altitudes where gravity is lower clocks speed up. The phenomenon follows directly from the assumption that energy has weight, through a simple argument. When a body is lifted it acquires some extra energy by virtue of the work expended to elevate it. If the energy that drives a clock (for example, elastic energy of a spring or vibrational energy of a balance wheel) also has weight, then additional work must be performed to lift it: crudely speaking, a ticking clock is heavier than an inert one. The extra work expended appears as enhanced internal energy which thereby induces the clock to run more energetically, that is, faster.

The time distortion effect is a completely general one and is really a property of time itself, not merely a mechanical shortcoming of clocks. It is a central prediction of Einstein's general theory of relativity because weighing energy amounts to checking the so-called equivalence principle—that gravity is locally indistinguishable from an acceleration. The effect is minute in the case of the Earth, but in certain astronomical objects such as black holes, it can become enormous.

In 1959 a modest precursor of the Vessot-Levine experiment was performed at Harvard University by R. V. Pound and G. A. Rebka. Very finely tuned gamma rays produced using the Mössbauer effect were shot vertically up a tower 22½ metres high and their frequency at the top compared with that at the base. The tiny shift of only a few parts in 10^{15} could be detected by compensating for it with the Doppler effect, which shifts the frequency of radiation from moving sources. The spacecraft experiment improves on this by probing much greater changes in the Earth's gravity than from the bottom to the top of a tower. The payload was projected 10,000 km into space atop a Scout D rocket launched from Wallops Island, Virginia. At this altitude the time distortion is as much as five parts in 10^{10}, well within the detection capabilities of modern atomic hydrogen masers.

The principle of the experiment was simply to compare the beats of the maser in space with two standard Earthbound masers. In practice there are great complexities involved because other more prosaic effects, such as ionospheric disturbances and Doppler shifting due to the spacecraft motion, have first to be taken into account. One vital requirement was to obtain accurate information about the spacecraft trajectory, because the time distortion effect is a function of altitude. The accuracy aimed for is about ± 100 m in position and ± 6 cm s^{-1} in velocity near apogee, though the authors admit that as yet substantially larger uncertainties exist. Further data reduction will be undertaken to improve the understanding of the trajectory, especially at low altitudes. On the basis of current data, the clock rate distortion predicted by the general theory of relativity is verified to two parts in 10^4.

The principle of equivalence can be checked in other ways, such as the Dicke-Eötvös experiment, which uses a type of balance at a fixed location on the Earth, and is found to be correct to one part in 10^{12}. If the principle is assumed correct, then the Vessot-Levine experiment can be used instead to check that the velocity of light is independent of direction by comparing the one-way and two-way light travel time from the ground to the spacecraft. In fact, the authors comment that there are a whole range of possibilities opened up by the use of high precision clocks aboard spacecraft.

About 70 years ago Einstein and others developed the theory of relativity by appealing to so-called *'Gedanken'* experiments in which observers undergo hypothetical experiences involving gravitational fields and different states of motion, while equipped with measuring rods and clocks. In those days spaceflight and super-accurate technology were merely a dream. Now, less than a century later,

P. C. W. Davies is a Lecturer in the Department of Applied Mathematics, King's College, London.

More news on SS 433

from A. C. Fabian

THE moving emission lines of SS 433 were one of the most exciting astronomical discoveries last year (see *News and Views* **277**, 267; 1979). Since the object became visible in the night sky this year many telescopes have been following its behaviour. At the Spring meeting of the American Physical Society in Washington, DC, Bruce Margon (University of California, Los Angeles) reported that the enormous variations in line position are due to the Doppler effect. He and colleagues at the University of California and elsewhere have been prominent in observing and unravelling this bizarre spectrum, and find that all emission lines visible in their spectrographs are split into three components. Those either side of the component at rest wavelength move in the opposite sense and are displaced by an equivalent velocity which varies up to $+52{,}000$ km s^{-1} and $-30{,}000$ km s^{-1}. The asymmetry is likely to be due to the transvese Doppler effect in emitting matter that is travelling (probably in two diametrically opposite directions) at about 80,000 km s^{-1}. The change in velocity represents an acceleration $\sim 1\,g$ over several weeks. The overall variation appears to recur on a period of 160 ± 3 days (or some multiple of that). The radial velocity curve passes through a cycle of ~ 104 d which is repeating this year within 2% (including some small but significant variations). The remaining part of the curve should be visible this summer.

Margon emphasised that this is the first time definite evidence has been found for large scale matter moving towards us at relativistic speeds—even the Paschen lines can be seen in the visible at maximum blueshift. Simply interpreting the radial velocity curve as due to a binary system leads to the picture of two masses of 2×10^9 M orbiting each other just beyond their respective Schwarzschild radii. Perhaps more plausible would be to consider that the emitting matter lies in two jets which are waving around with a period of 160 days. Radio astronomers find evidence for jets in radio galaxies, and relativistic matter squirting out of a galactic nucleus seems to be necessary in order to explain the superluminal expansion in many of these sources. SS 433 may represent a much scaled down galactic version of one of these nuclei. I currently favour a precessing neutron star as the underlying source of energy—Margon has noted that the inferred matter velocity in SS 433 is close to the velocity of escape from such an object. (As an aside it may be noted that SS 433 could be used by an interstellar civilisation to thrust them up to relativistic speeds!)

SS 433 would be visible in binoculars if its position in the galactic plane did not cause significant dimming of its light. Nevertheless, it is within the grasp of many telescopes and must represent one of the most spectacular objects visible. Special relativity can now be demonstrated at significant fractions of the velocity of light on something more than subatomic particles. The emitting mass in SS 433 exceeds 10^{24} *g*.

A. C. Fabian is Radcliffe Fellow in Astronomy, Center for Astrophysics, Harvard.

0028-0836/79/0279—0291$01.00