Astrophysics

Big, repulsive boson stars

Robert Walgate

THERE is normally little need to remark that all familiar stars — even quark stars and neutron stars — are made of fermions, particles of half-integral spin whose quantum statistics forbid them to enter the same quantum state. The result of this well-known fact is the 'degeneracy pressure' which keeps the fermions in different states like the electrons in an atom, and prevents even quite massive, relativistic stars from collapsing under gravity. But is it possible to conceive of a stable gravitating star made of bosons, the integral-spin particles which can form a single quantum state of, in principle, unlimited intensity? The theoretical Universe is, after all, beginning to be filled with exotic particles of many kinds from the bosonic 'superpartners' of the quarks and leptons to Higgs bosons and 'ghost' matter; it is conceivable that if boson stars exist then some of the supposed missing matter of the Universe could be in the form of such objects. In fact, as M. Colpi, S.L. Shapiro and I. Wasserman report (*Phys. Rev. Lett.* **57,** 2485; 1986), the answer seems to be yes.

Initial calculations supported by refined work with general relativity led R. Ruffini and S. Bonazzola (*Phys. Rev.* **187,** 1767; 1969) to suggest that boson stars would be possible. But by astronomical standards these early calculations gave the stars a tiny mass, of the order of the square of the Planck mass divided by the boson mass (around 300 million tons, or 10^{-19} solar masses for 1 GeV bosons), and a radius of the order of the Compton wavelength of its constituent bosons (1 fm or so for 1 GeV). It was difficult then to argue for a real astronomical role for such objects. The new work of M. Colpi *et al.* shows that the earlier conclusions — which assumed non-interacting bosons — can be drastically modified if the bosons have the slightest repulsive force among them.

The new work thus demonstrates that boson stars of in principle any mass might be assembled, depending on the interaction strength and mass of the constituent bosons. For example, it follows that a unit interaction strength (of the same order as the strong interaction) and a 1 GeV boson mass would lead to a boson star not of 1 fm, but of 100 m radius, and to the corresponding relativistic maximum mass of 0.1 solar masses. If the bosons were the putative axions of 10^{-5} eV mass, the star would be a crazy 10^{28} times bigger; whereas smaller interaction strengths could produce an object of, for example, the mass of Jupiter. This range indicates at least that boson stars must now be considered candidates to join the observers' menu of theoretical exotic stars.

Why is the interaction important? Essentially because any repulsive force of the order of magnitude of, or greater than, the gravitational force can keep the star buoyed up against gravity. If the force is short-range, at some critical mass gravity will overcome the repulsion and collapse will ensue; but the critical mass will be sensitive to the parameters of the repulsion. As the gravitational force is so weak (10^{-39} times the electromagnetic interaction between protons, for example), the assumption of even an extremely tiny force can have a dramatic effect. This is what Colpi *et al.* observe and develop in a full general-relativistic calculation.

Whatever the details of this calculation, the quantities and orders of magnitude involved are themselves illuminating. To set a baseline, the authors first assume non-interacting bosons. The radius, R, of a relativistic star (one near gravitational collapse, so that gravitationally bound particles have velocities near the speed of light) of such bosons will be of the order of the Compton wavelength of a single relativistic boson. Thus $R \sim 1/m$ in natural units, where m is the mass of the boson. (In natural units Planck's constant and the speed of light are taken to be unity. In such units, with masses in GeV, roughly the proton mass, lengths are approximately in femtometres.) But as the orbits are relativistic, R must be near the Schwarzchild radius GM, where G is Newton's gravitational constant and M is the mass of the 'star'. Combining these equations we find $M \sim 1/Gm$. Now we can replace G by its expression in terms of the Planck mass — the mass M_p such that the gravitational self-coupling GM_p^2 is roughly unity, and we find that the mass of the 'star' is $M \sim M_p^2/m$. This reproduces the bones of Ruffini and Bonazzola's result. The mass density of such a star would be M/R^3, or $M_p^2 m^2$, a gargantuan 10^{38} times nuclear density for 1-GeV bosons.

The first appropriate expression of Colpi *et al.* for the energy density of the interacting bosons, if ϕ is the boson field (or wavefunction, to use a more familiar name), is $m^2\phi^2 + \lambda\,\phi^4$. Here the first term approximates the mass and kinetic energy of a relativistic particle and the second is the assumed contact interaction term, which would arise, for example, if the bosons repelled one another by the exchange of a heavy intermediate particle. The question now is, what do we mean by 'small' interactions being important? By small we must mean that $\lambda\phi^4 << m^2\phi^2$, in other words that the interaction energy is much less than the kinetic or mass term. To extract λ from this inequality it is necessary to know the value of ϕ, the boson amplitude in the star. But the mass density of the star is $M_p^2 m^2$, as shown above, which must equal the boson-energy density. If λ is 'small' we can set the latter equal to $m^2\phi^2$. As a result, we see $\phi \sim M_p$, so that finally we get the limit on λ that $\lambda << (m^2/M_p^2) = Gm^2$. This means the self-interaction must be much weaker than gravity if its effect is to be negligible.

The next problem is to develop the theory with large λ, but the problem (S. L. Shapiro, personal communication) is that there are two dimensionless quantities to deal with in the calculations: λ and m/M_p. Hand-waving arguments thus fail to give any guidance, and it is necessary to solve the full relativistic equations. The resulting maximum boson star masses work out, for 'large' λ, to be around $M \sim 0.1 M_\odot \lambda^{1/2}/m^2$, with $M_\odot$ the mass of the Sun, rising as expected with the repulsion but falling as the square of the boson mass.

This is not the end of the story, however: refinements are still needed. Colpi *et al.* would like to deal with Higgs bosons, key elements of current unified field theories which in the empty (pre-inflationary) vacuum have an energy density much like that assumed above but with an attractive term (λ is negative). This leads to a condensation of Higgs field in the vacuum at the minimum of the energy density function (rather like the transition to superconduction in a superconductor). The condensate shortens the range of the weak interaction, giving the intermediate vector bosons the corresponding mass. Oscillations of the Higgs density are also allowed, and the corresponding waves are, in principle, observable, through wave–particle duality, as Higgs 'particles'. These are bosons, and could form boson stars — Higgs stars. Inside such stars, the Higgs field (which creates all particle masses) will vary, and the most intriguing physical possibilities arise. Unfortunately, Colpi *et al.* have so far been unable to solve the appropriate equations, which involve cubic as well as quartic terms, but work is in hand.

The group must also include the possibility of gauge forces such as colour and electromagnetism amongst the bosons. So far, Colpi *et al.* have assumed the particles to be neutral to a level equivalent to that of Ruffini and Bonizzola's neglect of possible λ terms. If the bosons were gauge charged, but on average neutral, the result would be an attractive force and the bose stars would undoubtedly collapse. So it will be necessary to consider non-neutral stars, those with a net gauge charge. Work on such stars, including the full Higgs terms, is now under way (S. L. Shapiro, personal communication). □

Robert Walgate is European Correspondent of Nature.