Boson stars in the centre of galaxies?

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Abstract. We investigate the possible gravitational redshift values for boson stars with a self-interaction, studying a wide range of possible masses. We find a limiting value of $z_{\text{lim}} \approx 0.687$ for stable boson star configurations. We can exclude the direct observation of boson stars. X-ray spectroscopy is perhaps the most interesting possibility.

1 Introduction

The idea of the boson star goes back to Kaup (1968). A boson star is a gravitationally bound collection of bosonic particles, arising as a solution of the Klein–Gordon equation coupled to general relativity. Many investigations of the possible configurations have been carried out; for reviews see Lee and Pang (1992), Jetzer (1992), and Liddle and Madsen (1992). For non-self-interacting bosons of mass $m$, the mass of a typical configuration is of order $m_{\text{Pl}}^2/m^2$, to be compared with a typical neutron star mass of $m_{\text{Pl}}^2/m_{\text{neutron}}^2$ which is about a solar mass. Here $m_{\text{Pl}}$ is the Planck mass.

The situation is very different if the boson stars have even a very weak self-interaction. Colpi et al. (1986) showed that the maximum mass of stable configurations is then of order $\lambda^{1/2}m_{\text{Pl}}^3/m^2$, where $\lambda$ is the scalar field self-coupling, normally assumed to be of order unity. Then boson star configurations exist with mass (and radius) similar to that of neutron stars, if the bosons, like neutrons, have a mass around 1 GeV. They can also be much heavier, should the bosons be lighter. We allow ourselves to consider a very wide range of possibilities for the boson star mass and radius. If boson stars exist, they provide an alternative explanation for stellar systems in which an object is inferred to have a high mass; conventionally, a ‘star’ with mass greater than a few solar masses is assumed to be a black hole.

We investigate the implications of assuming that the material from which boson stars are made interacts with neighbouring baryonic material and photons just gravitationally, as the relation between a visible galaxy and its dark matter halo. An example already existing in the literature is the boson–fermion star (Henriques et al. 1989, 1990), which is made up of bosons and neutrons interacting only gravitationally. However, while a galaxy halo can be described using Newtonian theory, boson stars close to the maximum allowed mass are general relativistic objects. This gives a new characteristic of such objects, a gravitational redshift (Schunck and Liddle 1997).
The boson star model is described by the Lagrange density of a massive complex self-gravitating scalar field \( \mathcal{L} = \sqrt{|g|} \left[ m^2_{\text{Pl}} R/8\pi + \partial_\mu \Phi^* \partial^\mu \Phi - U(|\Phi|^2) \right] /2 \), where \( R \) is the curvature scalar, \( g \) the determinant of the metric \( g_{\mu\nu} \), and \( \Phi \) is a complex scalar field with a potential \( U \). We take \( \hbar = c = 1 \). We want to have an additional global \( U(1) \) symmetry (conserved particle number), so we can take the following potential \( U = m^2 |\Phi|^2 + \lambda |\Phi|^4 /2 \), where \( m \) is the scalar mass and \( \lambda \) a dimensionless constant measuring the self-interaction strength. For spherically symmetric solutions we use the static line element \( ds^2 = \exp(\nu(r)) dt^2 - \exp(\mu(r)) dr^2 - r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \). The most general scalar field ansatz consistent with this metric is \( \Phi(r, t) = P(r) \exp(-i\omega t) \), where \( \omega \) is the frequency.

2 Gravitational redshift and detectability of boson stars

The maximum possible redshift for a given configuration is obtained if the emitter is exactly at the center \( R_{\text{int}} = 0 \). The receiver is always practically at infinity. For all other redshifts in between, we define the redshift function \( 1 + z_g(x) \equiv \exp(-\nu(x)/2) \), where \( x = \omega r \). A boson star with the maximum mass gives the highest value one can obtain from stable configurations (unstable configurations can yield very high redshift values) (Kusmartsev et al. 1991). We find that with increasing self-interaction values \( \Lambda := \lambda m^2_{\text{Pl}} / 4\pi m^2 \) also the maximal redshift value grows (Schunck and Liddle 1997). For \( \Lambda \to \infty \), we find the asymptotic value \( z_{\text{lim}} \approx 0.687 \).

The mass \( M \) of a boson star composed of non-self-interacting particles is inversely proportional to \( m \), while the mass of a self-interacting boson star is proportional to \( \sqrt{\lambda / m^2} \); see Colpi et al. (1986). Taking \( \lambda \sim 1 \), then for small \( m \) (to be precise, provided \( \Lambda > 1 \)) the self-interacting star is much more massive. For example, if we want to get a boson star with a mass of order \( 10^{33} \) g (a solar mass), then we need \( m \sim 10^{-10} \) eV for \( \lambda = 0 \), or \( m \propto \lambda^{1/4} \) GeV if \( \lambda \gg 10^{-38} \) (we see that the self-coupling has to be extraordinarily tiny to be negligible). In this example, the scalar particle has a mass comparable to a neutron, leading to a boson star with the dimensions of a neutron star. If we reduce the scalar mass further, to \( m \sim 1 \) MeV, then we find \( M \sim 10^{39} \sqrt{\lambda} \) g and \( R \sim 10^6 \sqrt{\lambda} \) km; this radius is comparable to that of the sun, but encloses \( 10^6 \) solar masses. These parameters are reminiscent of supermassive black holes, for example as in Active Galactic Nuclei; the mass–radius relation is effectively fixed just by the objects being relativistic. In all cases, the density of the boson stars makes their direct detection as difficult as in the case of black holes; in particular, they cannot be resolved in any waveband, cf. (Schunck and Liddle 1997).

However, even if boson stars cannot be directly resolved, their influence might still be visible if material in their vicinity is sufficiently luminous. It is necessary to find a certain amount of luminous matter within the gravitational potential of the boson star. This could, for example, be HI gas clouds as seen in galaxies. One might also expect accretion discs about boson stars, though there the luminosity could be dominated by regions outside the gravitational potential and the boson star would be indistinguishable from a black hole.
The most promising technique for observing supermassive boson stars is to consider a wave-band where they might be extremely luminous, e.g. X-rays. A very massive boson star, say $10^6 M_\odot$ is likely to form an accretion disk, and since its exterior solution is Schwarzschild it is likely to look very similar to an AGN with a black hole at the center. In X-rays, it has been claimed by Iwasawa et al. (1996) that using ASCA data they have probed to within 1.5 Schwarzschild radii. A boson star configuration provides a non-singular solution where emission can occur from arbitrarily close to the center. The signature they use is a redshifted wing of the Iron K-line. If such techniques have their validity confirmed, it may ultimately be possible to use X-ray spectroscopy to map out the shape of the gravitational potential close to the event horizon or boson star.

The rotation curves about a boson star (Schunck and Liddle 1997) show an increase up to a maximum with more than one-third of the velocity of light followed by a Keplerian decrease. If boson stars exist, then such enormous rotation velocities are not necessarily signatures of black holes. In Schunck (1997), a model with massless bosonic particles was applied to fit rotation curve data of spiral and dwarf galaxies.

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