ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research xxx (2017) xxx–xxx

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Dark matter, dark energy, and alternate models: A review

Kenath Arun [a,b,*], S.B. Gudennavar [c], C. Sivaram [c]

[a] *Department of Physics, Christ University, Bengaluru 560029, Karnataka, India*
[b] *Department of Physics, Christ Junior College, Bengaluru 560029, Karnataka, India*
[c] *Indian Institute of Astrophysics, Bengaluru 560034, Karnataka, India*

Received 18 December 2016; received in revised form 22 February 2017; accepted 28 March 2017

Abstract

The nature of dark matter (DM) and dark energy (DE) which is supposed to constitute about 95% of the energy density of the universe is still a mystery. There is no shortage of ideas regarding the nature of both. While some candidates for DM are clearly ruled out, there is still a plethora of viable particles that fit the bill. In the context of DE, while current observations favour a cosmological constant picture, there are other competing models that are equally likely. This paper reviews the different possible candidates for DM including exotic candidates and their possible detection. This review also covers the different models for DE and the possibility of unified models for DM and DE. Keeping in mind the negative results in some of the ongoing DM detection experiments, here we also review the possible alternatives to both DM and DE (such as MOND and modifications of general relativity) and possible means of observationally distinguishing between the alternatives.

Keywords: Dark matter; Dark energy; Cosmological constant; Dieterici gas; MOND; Modifications of general relativity

1. Introduction

One of the most unexpected revelations about our understanding of the universe is that the universe is not dominated by the ordinary baryonic matter, but instead, by a form of non-luminous matter, called the *dark matter* (DM), and is about five times more abundant than baryonic matter (Ade et al., 2014). While DM was initially controversial, it is now a widely accepted part of standard cosmology due to observations of the anisotropies in the cosmic microwave background, galaxy cluster velocity dispersions, large-scale structure distributions, gravitational lensing studies, and X-ray measurements from galaxy clusters.

Another unresolved problem in cosmology is that the detailed measurements of the mass density of the universe revealed a value that was 30% that of the critical density. Since the universe is very nearly spatially flat, as is indicated by measurements of the cosmic microwave background, about 70% of the energy density of the universe was left unaccounted for. This mystery now appears to be connected to the observation of the non-linear accelerated expansion of the universe deduced from independent measurements of Type Ia supernovae (Riess et al., 1998; Perlmutter et al., 1999; Peebles and Ratra, 2003; Sivaram, 2009).

Generally one would expect the rate of expansion to slow down, as once the universe started expanding, the combined gravity of all its constituents should pull it back, i.e. decelerate it (like a stone thrown upwards). So the deceleration parameter (q_0) was expected to be a positive value. A negative q_0 would imply an accelerating universe, with repulsive gravity and negative pressure. And the mea-

* Corresponding author at: Department of Physics, Christ Junior College, Bengaluru 560029, Karnataka, India. Fax: +91 80 4012 9222.
E-mail address: kenath.arun@cjc.christcollege.edu (K. Arun).

http://dx.doi.org/10.1016/j.asr.2017.03.043
0273-1177/

Please cite this article in press as: Arun, K., et al. Dark matter, dark energy, and alternate models: A review. Adv. Space Res. (2017), http://dx.doi.org/10.1016/j.asr.2017.03.043

surements of Type Ia supernovae have revealed just that. This accelerated expansion is attributed to the so-called *dark energy* (DE).

There are several experiments to detect postulated DM particles running for many years that have yielded no positive results so far. Only lower and lower limits for their masses are set with these experiments so far. The motto seems to be 'absence of evidence is not evidence of absence'. But if future experiments still do not give any clue about the existence of DM, one may have to consider looking forward for alternate theories (Sivaram, 1994a, 1999).

The best example of this is that of the orbit and position of Vulcan, which was theoretically inferred from the observation of Mercury orbit (Hsu and Fine, 2005). The deviation of its orbit, as predicted by Newtonian gravity, was attributed to the missing planet (DM). But the resolution of this discrepancy came through the modification of Newtonian gravity by Einstein and not by DM. This is unlike in the case of Uranus were the prediction and discovery were successful using DM (Neptune) theory (Kollerstrom, 2001).

2. Dark matter

2.1. Observational evidence for dark matter

The evidence for the existence of such non-radiating matter goes back to more than eighty years ago, when Zwicky (1937) was trying to estimate the masses of large clusters of galaxies. Surprisingly it was found that the *dynamical mass* of the cluster, deduced from the motion of the galaxies (i.e. their dispersion of velocities), in a large cluster of galaxies were at least a hundred times their luminous mass. This led Zwicky to conclude that most of the matter in such clusters is not made up of luminous objects like stars, or clusters of stars, but consists of matter which does not radiate (Zwicky, 1937).

Zwicky's observations were later confirmed by others and although he had overestimated the amount of DM it is now accepted as an established paradigm. Later observations starting about forty years ago, and continuing till now also revealed unmistakably that even individual galaxies like our Milky Way are dominated by DM (Rubin and Ford, 1970; Rubin et al., 1980). We know this for galaxies because it turns out that objects orbiting the galaxy at larger distances from the galactic centre move around more or less the same velocity as objects much closer to the centre, contrary to what is expected (Jones and Lambourne, 2004).

The rotational velocity should drop as $v_c \propto r^{-1/2}$, like in solar system. But at large distances, rotational curve becomes flat, i.e. $v_c \approx$ constant. This is valid for all spherically symmetric system and is valid at large distances. This gives information that mass is still growing even after light dies out ($M \propto R$). Indeed, as much as 90% of the galaxy mass is due to DM. This can only be accounted for if the mass progressively increases with radius as we move out further and further away from the central region. But this matter does not radiate as most of the light is from the central region. So the conclusion is that 90% of the galaxy is DM.

This seems to be universally true for all types of galaxies. Even in dwarf galaxies, the motion of their stars indicates the presence of DM (Bell and de Jong, 2001; Stierwalt et al., 2017). Even the 'missing satellite problem' (Moore et al., 1999; Nierenberg et al., 2016), which arises from numerical cosmological simulations that predict the evolution of the distribution of matter in the universe, could be attributed to the fact that many dwarfs have a huge amount of dark matter but very few stars, making them difficult to detect due to their inherent faintness.

Cosmological models predict that a halo the size of our Galaxy should have about 50 dark matter satellites with circular velocity greater than 20 km s^{-1} and mass greater than 300 million solar mass within a 570 kpc radius. But the actual number of observed satellites is much lesser. The difference is even larger in the case of galaxy groups like the Local Group. (Klypin et al., 1999)

Recently, Beasley et al. (2016) reported measurements of ultra diffuse galaxies (UDGs) which have the sizes of giants but the luminosities of dwarfs. Deep imaging surveys of Fornax, Virgo, Coma and the Pisces-Perseus superclusters have revealed substantial populations of faint systems that were hidden from earlier surveys. Coma cluster for instance consists of galaxies with sizes similar to that of the Milky Way, but stellar luminosities similar to that of dwarfs. Measurements from a UDG (VCC 1287 in the Virgo cluster), based on its globular cluster system dynamics and size indicates a virial mass of $\sim 8 \times 10^{10}$ solar mass, yielding a dark matter to stellar mass fraction of $\sim$3000 indicating that about 99.96% of the galaxy is dark matter (Beasley et al., 2016).

Apart from velocity distribution of galaxies and galaxy clusters, there are other evidences pointing to the presence of dark matter. Extended emission in X-ray observations of clusters of galaxies indicates presence of hot gas distributed throughout the cluster volume (Ferrari et al., 2008). If the gas is in virial equilibrium within the cluster we have:

$$kT \sim \frac{1}{2} m_p v^2 \tag{2.1}$$

where the thermal velocity is $\sim$1000 km s^{-1}. This implies a temperature of $T \sim 6 \times 10^7 K$, which produces bremsstrahlung emission in X-rays. The total emission power density, integrated over all frequencies is given by:

$$\varepsilon_{ff} = 1.4 \times 10^{-27} Z^2 n_e n_i T^{1/2} \tag{2.2}$$

where n_e, n_i are the number density of electrons and ions respectively, Z is the atomic number and T is the temperature.

From X-ray observations, luminosity can be measured, which depends on density, temperature and volume of the cluster. The mass required to hold hot gas in cluster estimated requires vast amount of DM. Hot gas itself