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Dark Matter in the Universe

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Abstract. Presence of dark matter (DM) was inferred from the rotation curves of galaxies in the 1980s. Direct evidence for the existence of DM has been obtained only recently. I review these recent observations of DM in the laboratory and in high energy cosmic rays. I survey the properties of dark matter inferred from these experiments, the main particle physics models of DM and comment on the viability of these models in the light of experimental observations.

Keywords : (cosmology:) dark matter – ISM: cosmic rays

1. Introduction

The first evidence of DM was given by Zwicky in 1933, who observed the velocity distribution of galaxies in the Coma cluster. By applying virial theorem, he inferred the presence of non-luminous gravitating matter. Major quantitative evidence of DM was obtained by measuring the rotation speed of neutral hydrogen gas in galaxies as a function of radial distance (Rubin et al. 1985). The rotation curves of a large number of galaxies have been obtained. These indicate that to provide the centripetal force necessary to maintain the observed rotation speeds of 200 km/sec, more than 90% of the mass in galaxies should be in a non-luminous form of matter. From the rotation curve of the Milky way it has been inferred (Sakamoto et al. 2003) that at the location of the solar system the DM density is 0.2–0.4 (GeV/c^2) cm^{-3}. This number is important in determining the cross section of DM interactions in the terrestrial direct detection experiments.

The most precise measurement of the amount of DM in the universe at cosmological scales comes from the observation of the cosmic microwave background (CMB) (Komatsu et al. 2011). At the epoch of photon decoupling (at redshift z∼1100) when

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the universe becomes transparent to photons, the photons climbing out of the local gravitational potential of the DM in the surface of last scattering undergo gravitational redshift. This inhomogeneity in the last scattering surface is seen as the angular anisotropy of the CMB. The first peak in the angular spectrum of CMB anisotropy is due to the oscillations of the baryon-photon plasma. The amplitude of this peak gives the density of baryons in the universe and the amplitude of the third peak gives the information about the amount of dark matter. The seven year data from WMAP (Komatsu et al. 2011) gives the baryon and DM densities of the universe as $\Omega_b h^2 = 0.022 \pm 0.0005$ and $\Omega_{DM} h^2 = 0.1123 \pm 0.0035$ respectively, where $\Omega \equiv \rho/\rho_c$, $\rho_c = 1.05 \times 10^{-5}$ (GeV/c^2) cm^{-3} is the critical density which gives a flat universe and $h = 0.74 \pm 0.02$ is the Hubble expansion rate in units of 100 (km/s)/ Mpc.

The density of the universe is close to the critical density within a few percent and the density distribution between baryonic matter, DM and dark energy (or the cosmological constant) is $\Omega_b \simeq 5\%, \Omega_{CDM} \simeq 20\%$ and $\Omega_{DE} = 75\%$. The nature of dark energy (a form of energy with negative pressure) whose existence is inferred from the acceleration of Type I supernova (Reiss et al. 2007) remains unknown. The situation is slightly better for DM where a number of direct detection and observations from high energy cosmic rays have narrowed down the parameter space for interaction cross section and mass of these particles.

In the hot big bang model of cosmology it is noticed that if particles have weak interaction cross sections and they decouple just when the temperature goes below their mass, they escape annihilation and have a density in the present universe of the order of the critical density. This leads to the favourite WIMP (weakly interacting massive particles) paradigm about the nature of DM (Kolb & Turner 1990).

Observations of cosmic rays from satellite based detectors like in PAMELA (Adriani et al. 2010) and FermiLAT (Abdo et al. 2009) experiments have shown a much larger flux of positrons than what is expected from the secondary production of positrons from the collision of primary cosmic ray protons with ambient matter in the galaxy. The observations of positron excess at energies up to 100 GeV suggest that a possible source of these positrons is DM annihilation in the galaxy. However there are two puzzling aspects to this interpretation. The annihilation cross section of dark matter needed to explain the positron excess is 3 to 4 orders of magnitude larger than the weak interaction cross section which gives the correct dark matter relic density in the hot big bang cosmology. The second puzzle is that there is no corresponding excess seen in the anti-proton (Adriani et al. 2009) or gamma ray flux (Abdo et al. 2009) which challenges particle physicists to come up with models in which DM annihilates into electron-positron pairs and little else.

In the following sections I summarize the calculation which establishes WIMPS as natural dark matter candidates which have the correct relic density from the standard hot big bang cosmology. I then survey the results about constraints on DM from terrestrial experiments and from cosmic rays.

2. Weakly interacting massive particles as DM

In the early universe all beyond-standard model particles will be in thermal equilibrium with standard model particles as long as their mass $M < T$. When the temperature drops below M, the number density of those particles whose annihilation rates are larger than the Hubble expansion rate H, goes down exponentially $n \propto \exp(-M/T)$. If particles are weakly interacting then it may be possible that at some temperature just below their mass their annihilation rate goes below the expansion rate and they decouple or "freeze-out". Below this decoupling temperature the number density of these particles dilutes with the expanding universe at the same rate as the light standard model particles. The lower the annihilation cross section, the earlier the particles freeze out and the larger will be their present relict density. A detailed calculation (Kolb et al. 1990) shows that the density of DM in the present epoch is related to their annihilation cross section as

$$\Omega_{DM} h^2 = \frac{0.3 \times 10^{-37}\ \mathrm{cm}^2}{\langle \sigma \rangle} \tag{1}$$

This gives rise to the WIMP paradigm that particles with weak interaction cross sections $\sigma \sim 3 \times 10^{-37}\mathrm{cm}^2$ can naturally explain the WMAP measurement of $\Omega_{DM} h^2 \simeq 0.1$.

3. Indirect detection through cosmic rays

Satellite based experiments like PAMELA and FermiLAT have observed e^+, e^-, p and $\bar{p}$ of energies up to 100 GeV and their findings have raised some perplexing questions about the nature of DM. PAMELA observed positrons with flux $\Phi_{e^+} \simeq 2\times10^{-5}\mathrm{m}^{-1}\mathrm{s}^{-1}$ GeV^{-1} Sr^{-1} at energies $\sim$100 GeV (Adriani et al. 2010). This is an order of magnitude larger than the expected positron flux from secondary cosmic rays. One idea is that DM in the galaxies annihilates into standard model particles and contributes to the positron flux of cosmic rays. A major problem with this is that to explain the observed positron flux the annihilation cross section of DM should be $\sigma \sim 10^{-33}$ cm^2 which is four orders of magnitude larger than the WIMP cross section needed for the observed relic density. This problem can be solved by invoking a non-perturbative phenomenon called the Sommerfeld effect which predicts that if there is a long-range attractive force between incoming particles then the annihilation cross section can be enhanced by up to four orders of magnitude. A particle physics model based on supersymmetry which invokes the Sommerfeld effect to reconcile PAMELA observations with relic density observations has been constructed (Mohanty et al. 2010). This model also explains the non-observation of excess anti-protons (Adriani et al. 2009) or excess gamma rays (Abdo et al. 2009) above the expected cosmic ray background. Observation of cosmic rays at higher energies can test such particle physics models of DM.

4. Direct detection in terrestrial experiments

There are many laboratory based experiments for detection of DM like DAMA, Cogent, Xenon, CDMS etc. These experiments look for a scattering event of nuclei by DM. In detector masses of 100 kg and with the estimated local density of DM of 0.3 GeV/(c^2cm^3) and with weak interaction cross sections one expects a few scattering events in a year. The main difficulty in these experiments is to separate the non-ionizing DM scattering from the ionizing scattering by radioactivity in the background. One experiment which avoids the problem of background elimination is DAMA (Bernabei et al. 2008) which looks for an six-monthly modulation of the DM signal which is expected due to the earths orbit in the galactic DM 'wind'. Over a period of 13 years of observations DAMA experiment has reported such a modulation which is not expected from the radioactive background. The results of DAMA have not yet been corroborated by any other experiment. In case DAMA observations are verified by other ongoing experiments, one model which can explain the DAMA signal is the dipolar DM model (Masso et al. 2009) where the DM is a $\sim$10 GeV/c^2 mass particle which does not have a charge but which posseses magnetic moment of $\mu \simeq 10^{-6}\mu_B$. Once again the validity of such theoretical models will be tested by ongoing direct detection experiments.

5. Conclusions

There are many tantalizing hints of the particle nature of DM in cosmic ray and direct detection experiments. Dark matter particles are expected to be produced at the LHC. The cross correlation of these different experiments with theoretical models is an exciting area of research and likely to remain so in the near future.

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