Prospects in Experimental Particle Astrophysics

by

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Abstract

The application of standard particle physics techniques to cosmological and astrophysical questions has given rise to an exciting new area of physics research known as particle astrophysics. In the discussion which follows, I would like to summarize some of the key elements of this research area and indicate to you some of the experimental directions in which we might see some progress as new experimental facilities are brought on line over the course of the next several years.

Introduction

The current study of the origin of the universe has evolved into a picture which seems to be adequately explained by a theory that we call the Standard Big Bang Cosmology (SBBC). This theory is the astrophysics analog to the "Standard Model" of particle physics. SBBC has evolved over many years and has been fairly successful in explaining the universe as we see it today, but as in any theory, there are always inconsistencies to address and anomalies to discover. Further, as this theory has evolved back to the earliest epochs, it has been merged with the "Standard Model" to produce a theory which eventually might become, "Theory of Everything" (TOE). One of the goals of particle astrophysics research is to address both the experimental and theoretical questions necessary to eventually arrive at such a TOE.

I would like to start off our discussion here by outlining several of the most significant features of our current picture of the universe and then to raise a few of the remaining questions we have about this picture. Following the presentation of these general points, I will move to a discussion of the whereabouts and form of the missing matter apparently indicated by these data and how one might go about searching for this "Dark Matter" (DM). In searching for DM I will talk briefly about a specific new particle astrophysics observatory presently under construction at the Gran Sasso Laboratory in Italy called MACRO and how it may shed further light on several of the pending experiments.

Basic Elements of Particle Astrophysics

There are volumes of information which fall into this category, however, I will be selecting only a few of those points which I feel are particularly important to the discussion being developed here.

First of all, the major experimental element in the picture of the universe as we know it today is the overall level of observed luminous matter. From a vast body of work performed by our astronomer colleagues, it is generally accepted that we are able to account for only about 20 % of the matter necessary to provide for a **closed** universe. [1] *Apriori*, this might not appear to be too much of a problem, since who's to say that our universe "should" be closed? However, I will be coming back to this point a bit later as I investigate some of the other elements of this SBBC picture. To further complicate things regarding masses and abundances, current theories of Big Bang cosmology coupled with the Standard Model seem to agree well with the elemental abundance observed in this luminous matter. [2] When

$$\Omega = \frac{\rho_{observed}}{\rho_{critical}} = .2$$

then

$$\begin{array}{ccccccc} H & : & {}^4He & : & D + {}^3He & : & {}^7L_i \\ 1 & : & \frac{1}{4} & : & 10^{-5} & : & 10^{-9} \end{array}$$

which is in fairly good agreement with the experimental situation.

Another feature of our current picture of the universe is that it appears to be expanding uniformly. This expansion rate is called the Hubble constant or Hubble velocity and is defined as follows:

$$H \equiv \dot{R}/R = 100km/sec/Mpc$$

(1pc = 3.09 x 10^{16}m) where R is the radial distance to a given object. The Hubble constant is generally accepted to have a value of 100km/sec/Mpc and this expansion rate is used by astronomers as a standard distance measure in astronomical observations.

A third point in this picture is that a measure of the cosmic ray background radiation remaining from the Big Bang is consistent with 3° black body radiation and is extremely isotropic with

$$\frac{\delta T}{T} \leq 10^{-4}$$

where δT is the deviation from the black body temperature in a particular region of the sky from the average black body temperature. [3,4]

Lastly, it has been clearly demonstrated at this school and at many other conferences and work-shops over the past few years, that the Standard Model works extremely well in explaining phenomena up to energies of several hundreds of GeV for the strong, electromagnetic and weak interactions. Using these points as a base, we can now investigate the ramifications that naturally follow from these observations and see what predictions or inconsistencies they may infer.

Problems with the SBBC

There are a few key questions which have arisen concerning the SBBC that have shed some new light on this theory. First of all, why is our universe matter dominated? The SBBC produces equal amounts of matter and antimatter during the early epochs and this symmetry must be broken through the intervening period following the Big Bang til the present. This problem was taken care of by adding baryon number violation, charge conjugation symmetry violation and CP violation into the SBBC.

The next question needing to be addressed is, "Why is the universe so homogeneous" ($\frac{\delta T}{T} \leq 10^{-4}$)? To handle this problem the concept of the "inflationary universe" was introduced.[5] In this version of the SBBC during the early epochs, the universe found itself in a "false vacuum" with a large vacuum energy, α, then in the subsequent transition to the "real" vacuum, the radius of the universe expanded rapidly as

$$R(t) \sim e^{\alpha t}.$$

If this expansion persists for any significant period of time, the result is an extremely "flat" and "isotropic" universe,[6] were Ω not very near one throughout this inflationary period, any deviations would have been greatly exaggerated in the process. [7]

This brings us to the last major puzzle in this picture of the universe. After taking care of the isotropy question by introducing inflation, we now see that another "natural" consequence of this theory is that the relative mass density of the universe is identically equal to one

$$\Omega = 1.00....$$

However, if this is true, where is the rest of the matter/energy, and how has it managed not to affect the observed elemental abundances? We might also ask is there any additional evidence to support the assertion that the universe is closed? Here there are two bits of experimental information which appear to support such an assertion.

The first is found in the study of the velocities of stars in spiral galaxies. Here a curious effect is noted in the rotational velocity curves of stars as a function of their radial distance from the center of these galaxies. The velocities appear to flatten at large radii[8] instead of monotonically decreasing to zero as you reach the edges of these galaxies. Such an effect in rotational velocities could arise from the existence of additional undiscovered non-luminous matter that could act gravitationally on the luminous matter in these galaxies.[9]

A second indication for additional matter arises in the SBBC discussions of how we can develop the clustering of galaxies that we see today? Once again our explanation of this effect includes the introduction of non-luminous gravitationally interacting matter in the universe to act as nucleation sites for these structures.

In summary, it appears that several problems with the SBBC can be addressed at some level by the introduction of non-luminous, weakly interacting Dark Matter into the universe. This matter, however, would then constitute a substantial amount of the universe, so the question remaining is where is this material hiding and how can we go about detecting its existence?

Dark Matter

To account for this missing material needed for closure, we have postulated the existence of a new type of matter, "Dark Matter". The main characteristics of this material is that it is non-luminous neither emitting or absorbing electromagnetic radiation, it is gravitationally and weakly interacting and it is primarily non-baryonic (for if it were strongly interacting baryonic material, it would have altered the nuclear abundances discussed earlier).

From the particle physics side of this study, there are several candidates which fit the requirements of DM quite nicely.

Axions

Axions have been predicted to solve the strong CP violation puzzle [11] and providing that their masses and abundance were right, could be a strong candidate for Dark Matter. These light pseudoscalar particles have been searched for over a wide range of masses from 10's of GeV to eV's and as yet no direct evidence for their existence has been found. At present the mass range $\sim 10^{-5}$eV seems to be the most likely region yet to be explored fully.

Lightest Supersymmetric Particles

Lightest Supersymmetric Particles (LSP) have been predicted by many of the current Supersymmetric Theories.[12] These particles would be stable, weakly interacting neutral particles with masses in the range of 10's – 100's GeV. Once again, providing the combination of masses and abundances are correct, these particles could satisfy our DM requirements. Possible candidates for the LSP include the photino, sneutrino and higgsino. These objects would mainly show themselves through annihilation processes since they are stable against further decay. The end results of these annihilations would be pairs of high energy electrons/positrons or neutrino/antineutrinos which could then be observed with conventional particle detectors.

Heavy Neutrinos

Massive neutrinos have long been a possible candidate for the missing matter in the universe. Since there are many neutrinos left from the earlier epochs of the Big Bang, should they have a small but non-zero mass (of order 10's of eV), they could easily account for the Dark Matter we are looking for. Several on-going searches have been undertaken to measure the mass of the neutrino in nuclear β decays. The latest results from those very difficult experiments are lower limits on the $\overline{\nu}_e$ mass of a few eV.[13] This mass limit coupled with our knowledge of ν abundances in the cosmic ray background start to remove the massive ν from the realm of DM candidates, but I mention it here for completeness.

Monopoles

Lastly, an exotic beast arising from Grand Unified Theories, the magnetic monopole, could also satisfy our DM needs for closure. These particles arise during the cooling of the universe through the Grand Unification phase and have masses typical of the unification energy scale ($\sim 10^{16}$ GeV). There is much conjecture as to the expected abundances of these particles based on GUT theories, however, these objects are weakly interacting and stable, so they could be the source of the missing matter we are in search of.

Summary

Each of the above particles has been the subject of on-going searches for some time. Their existence and properties are key elements to our understanding of the physics of the Standard Model, and so have been sought after long before the concept of DM became fashionable. Be that as it may, those previous searches now form the starting point for a whole new array of searches which couple strongly astrophysical and particle physics phenomena, opening up an entirely new realm of experimental physics.

Common to all of these searches for exotic DM candidates is the need for large (area/volume), high precision and low background detectors. A detailed discussion of many of these techniques is presented in an excellent review paper by J.R. Primack, D. Seckel and B. Sadoulet. [9]. These experimental requirements have ushered in a new wave of large underground facilities designed to search for these and other exotic objects, and several of these detectors are due to be brought on line in the near future (MACRO, Superkamiokande, LVD, Grande etc).

The MACRO Detector

In the remainder of this presentation, I would like to take the opportunity to describe the work being carried out at the Gran Sasso Laboratory by a group of U.S. and Italian scientists working one such experiment, MACRO. The list of institutions working in the MACRO collaboration appears in Reference 10; and the data that I will present in this section is being presented on behalf of this group.

The MACRO (Monopole, Astrophysics and Cosmic Ray Observatory) detector is a large underground detector composed of streamer tube tracking chambers, scintillation counters, track etch detectors and passive absorber all aimed at studying monopoles, astrophysical sources of neutrinos and other exotic cosmic rays. MACRO is located in hall B of the Gran Sasso Laboratory, L'Aquila, Italy approximately 120km from Rome. The experimental hall is located 963m above sea level and is shielded by a rock overburden averaging 3800 meters of water equivalent.

The MACRO detector, shown in Figure 1., is composed of nearly 500 scintillation counters (containing 900 tons of scintillator), over $15000m^2$ of streamer tube tracking chambers and over $1000m^2$ of track etch detector. These elements are arranged in six supermodules, each 9m high, and 12m x 12m horizontal area. The total detector fills a volume 9m x 72m x 12m. A detailed figure showing the distribution of these elements inside a supermodule is shown

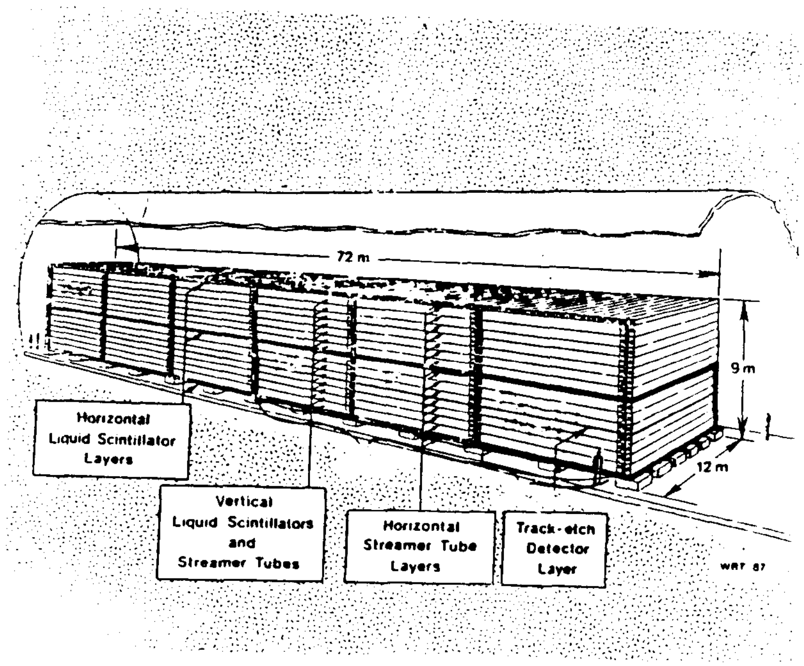

FIGURE 1. Layout of the MACRO detector. Shown are the six double decker supermodules. At this time the bottom portions of these six modules have been fully constructed and supermodule one has been in operation for over a full year. Modules 2-6 are expected to be brought on-line later in 1991 and the upper portion of the detector is scheduled for completion sometime late in 1992.

in Figure 2. The detector has an overall acceptance for isotropic phenomena of $10^4 m^2 sr$.

Within each supermodule are ten planes of streamer tube chambers, interspersed with low activity crushed rock absorber and surrounded by the liquid scintillation counter system. In the middle of the absorber stack is located an additional plane of track etch detectors composed of CR39 and LEXAN to identify heavily ionizing components of the observed cosmic rays. The streamer chambers are readout both on the anode wires and a set of stereo angle cathode strips to provide space points for tracking. The chambers have a resolution of 1.1cm in the wire view and 1.2cm in the strip view. With ten planes of tracking chambers, we achieve an angular resolution of 0.1^o; which is to be compared to the typical multiple scattering suffered by a high energy muon penetrating the rock overburden of 0.6^o.

The liquid scintillation counters are filled with a custom mixture of high purity mineral oil, pseudocumene, wave length shifters and anti- oxidents to produce high light yields with relatively long attenuation lengths. The typical response of one of our 12m x .75m x .25m counters to a minimum ionizing particle passing through its center is approximately 400 photoelectrons, with a typical light attenuation length of $> 12m$. The relative timings and amplitudes of the fast pulses emitted from these counters are measured by a system of ADC's and TDC's. For the longer developing pulses characteristic of monopoles, we also record the wave forms of groups of four to eight tanks using wave form digitizers of both 20 and 100 Msamples/sec.

The detector and its accompanying electronics has been designed to produce a variety of triggers to initiate the readout of the device. Both the streamer tube and scintillator systems have muon and slow monopole triggers, while the scintillation system also has additional triggers for stellar collapse neutrino bursts and fast monopoles as well. The times of recorded events are determined by a rubidium-cesium clock accurate to 1nsec.

Based on the operation of the first supermodule of this detector for over one year, we have measured several performance specifications of the detector. We have an angular resolution from our tracking system of 0.1^o and a time-of-flight resolution for μ's through the scintillation counters of $\sigma_t \sim$ 1.7nsec. In addition, after correcting for μ pathlength differences for cosmic rays traversing

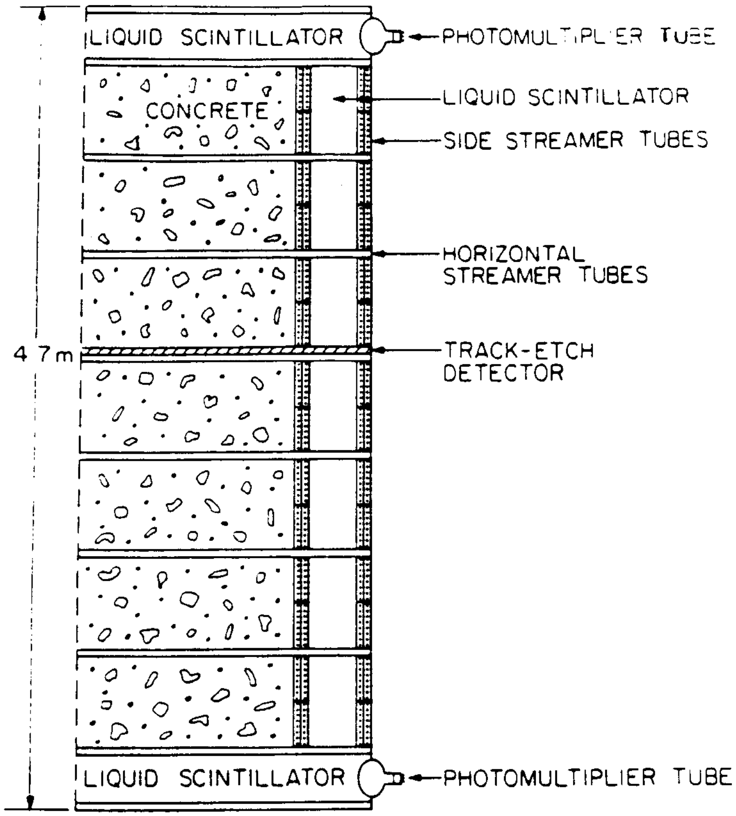

FIGURE 2. The cross section detail of the bottom portion of a MACRO supermodule. The upper part of the module is planned to be a shell of scintillation counters and streamer tube tracking chambers surrounding a large open volume on top of the existing structure. This open region is planned to be used for the addition of future detectors (eg. transition radiation detectors, analyzing magnets,..).

the detector, we observe an energy resolution in the scintillation counter system of

$$\sigma_E = 0.3/\sqrt{E} \ \ (E \ in \ MeV).$$

Since February of 1989, we have recorded over 4700 hrs. of data with the bottom portion of supermodule one. These data were grouped in two runs (Feb.- May 1989 and Nov. 1989 - May 1990) During these runs we have operated this module at over 80% live time efficiency and have recorded over 5 x 10^6 cosmic ray muons passing through the detector. As the rest of the detector is completed and brought on line over the course of the next year or so, we anticipate that MACRO will be able to probe deeply into a number of exciting research areas.

The main thrusts of the MACRO program are:

- sensitive search for magnetic monopoles
- neutrino astronomy
- study of cosmic ray muons
- searches for other exotic particles in cosmic rays

(eg. weakly interacting massive particles (WIMPs,DM)

Today's discussion will focus on only the two of these elements that tie into our earlier discussions on DM candidates. First I will discuss MACRO's ability to search for magnetic monopoles and indicate what this tells us about those beasts as DM candidates and then I will move over to a discussion of using MACRO to search for DM WIMPs.

Magnetic Monopoles

A primary goal of the MACRO experiment is to undertake a sensitive search for super heavy magnetic monopoles remnants of the Big Bang. These objects would be moving at relatively slow velocities ($\beta \sim 10^{-3}$) with respect to the earth and would be identified in our detector through our multiply redundant detector system. A monopole passing through MACRO would produce a slowly developing set of pulses in the scintillation counters and streamer tube chambers being traversed (x 10^3 longer in duration than the corresponding pulses produced by μ's) and they would leave ionization energy losses in each of the detector elements characteristics of a heavy, slow-moving neutral particle with magnetic charge.[14]

In searching for magnetic monopoles there are two indirect limits on their abundances which can be used as guide posts to gauge the sensitivity of our searches. The first of these is called the "Parker Limit".[15] The "Parker Limit" is an indirect limit placed on isotropic, heavy monopole abundance based on the existence of intergalactic magnetic fields. The argument states that should the abundance of monopoles be larger than this limit, then these monopoles would gradually deplete the energy stored in these fields resulting in a magnetic field free region. By constructing a very simple model for replenishing the magnetic fields in the presence of these fluxing monopoles, we can infer a limit on their abundance. Arguments originally outlined by Parker [15] and later refined by Parker,Turner and Bogdan [16] yield a flux limit of

$$\phi_{Parker} \leq 1.3 \times 10^{-15} cm^{-2} sec^{-1} sr^{-1}$$

in order for monopoles not to exhaust these magnetic field.

The second limit on their abundance can be related directly to the question of the missing mass in the universe. We can ask what density of monopoles would be necessary to provide for the missing DM necessary to close the universe. Using a monopole mass of $10^{16} GeV/c^2$ and assuming they are moving with velocities of 10^{-3}c results in a flux limit for monopoles of

$$\phi_{closure} \sim 5 \times 10^{-15} cm^{-2} sec^{-1} sr^{-1}.$$

The MACRO detector has been designed to be large enough to reach and surpass both of these limits in several years of running. As a result, it will be the first detector capable of pushing the limit for the monopole content of the missing DM to a level of a few percent of the critical density.

Over the last two data taking runs we have carried out a monopole search using the scintillation counter systems in module one to investigate monopoles from a β of 2 x 10^{-4} to 10^{-2}. A monopole passing through the apparatus will have slowly developing pulses depending on the monopole velocity in each of two struck scintillation counters in the detector. Furthermore, the time interval between those successive hits will also be correlated with the monopoles velocity. Hence, in making a two face coincidence measurement of monopole fluxes, we are able to use the time development of signals and time-of-flight measurements to constrain our analysis. The efficiency as a function of β of our two triggering schemes based on the temporal development of the monopole signals in the scintillation detectors is shown in Figure 3. This figure shows our trigger sensitivity for detecting slow monopoles in the velocity range $\beta < 5 \times 10^{-3}$ using a specially designed "leaky integrator" circuit to detect the slowly developing monopole in a single scintillator counter, trigger one, and our sensitivity for triggering on faster monopoles in the range 1.5×10^{-2} *to* 5×10^{-3} using a simple overlap coincidence between delayed signals from two faces of the detector, trigger two.

During our first run we observed 394 type one triggers and 930 type two triggers for monopoles in 80 days of running. These events were then further analyzed and signals were required to be consistent with a monopole traversing the detector and striking two faces of the detector. From this analysis, we found no events in the trigger sample from either data taking run surviving. Hence, we are thus able to set an upper limit on the isotropic flux of the monopoles through our detector during these observational periods. For the 1989 data we set a limit of

$$\phi \leq 4 \times 10^{-14} cm^{-2} sec^{-1} sr^{-1} \quad (90\% CL).$$

In the subsequent 89-90 running we have accumulated another 3021 hours without any monopole candidates triggering our detector surviving our analysis. This yields a combined upper limit on monopole flux of

$$\phi \leq 1.45 \times 10^{-14} cm^{-2} sec^{-1} sr^{-1} \quad (90\% CL).$$

These results are summarized in Figure 4. which displays the current "best limits" on searches for heavy monopoles from the various experiments along with the "Parker" bound. Also shown on this figure is the anticipated flux limit from the operation of the full MACRO detector after five years of operation.

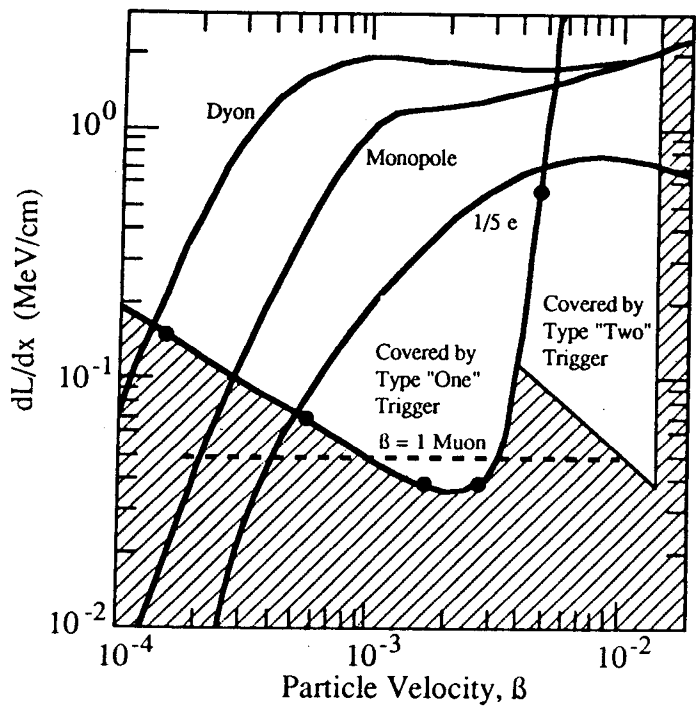

FIGURE 3. Light output as a function of the relative velocity of a monopole($\beta = v/c$) for the two velocity ranges covered by the MACRO monopole trigger. The solid curves represent the 90% efficiency boundary for both trigger types. The points shown represent measurements of the efficiency of type "one" triggers using a LED monopole pulse simulator. Also shown in the figure are the expected light levels for the passage of a Dyon, monopole and 1/5 e charged particle through a scintillation counter.

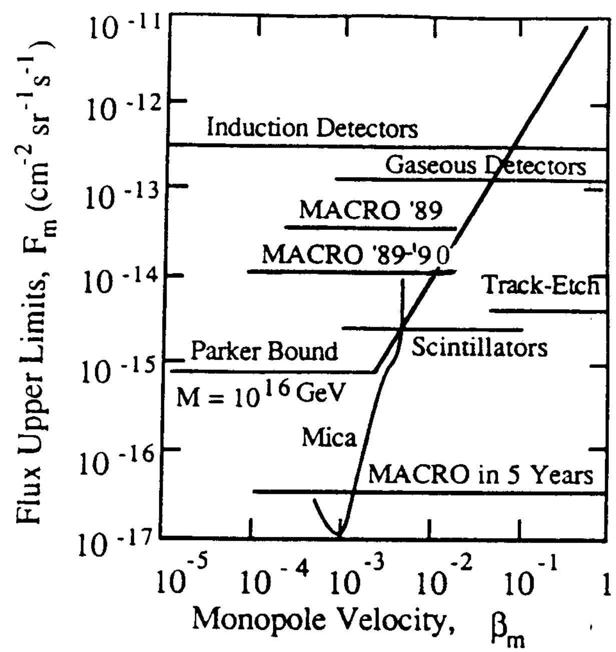

FIGURE 4. Present upper limits on the flux of GUT magnetic monopoles of unit Dirac charge versus monopole velocity(β_M). The various curves represent the current "best" values obtained by each of the above cited detector techniques(gaseous detectors, induction detectors, scintillation detectors and track etch detectors). Also shown are the results from MACRO for the running of the first supermodule as well as the expected sensitivity of the completed experiment.

WIMPs

The MACRO detector is also sensitive to other forms of Dark Matter. In particular as discussed earlier, any of these objects which can undergo annihilation with an appropriate anti-WIMP, and produce high energy fermion pairs subsequently resulting in the emission of high energy neutrinos could then be detected with MACRO. In the work presented here we have studied the class of WIMPs (neutrinos, sneutrinos, photinos, higgsinos) which can random walk through the universe and collect gravitationally in the stars and planets. Once they have been captured, they are gravitationally bound until they annihilate on a suitable anti-particle. An equilibrium is eventually reached where the rate of annihilations equals the capture rate of these heavy WIMPs in these stars.

In MACRO we have undertaken a search for upward going muon neutrinos coming from the annihilations of these WIMPs either in the earth or sun. These neutrinos could interact with the earth below producing a charged current neutrino interaction yielding an upward going μ which could then be easily seen in the MACRO detector.

Searching for evidence of WIMP annihilations in the sun and/or the earth presents two different sets of experimental challenges for the MACRO detector. Searches using the sun are aided by the sun's large size, strong gravitational attraction and small effective source solid angle but are undermined by the fact that we can only search during the night (upward going muons), that the mass of WIMPs of interest are large compared to the masses of the nuclear constituents of the sun and hence, more difficult to trap and lastly the source is far away so the rates are reduced. Detection of WIMP annihilations from the earth on the other hand is aided by the close proximity of the source and detector, the ability to search 24 hrs/day and the closer match between WIMP masses and the masses of a typical nuclear material making up the earth (10's of GeV/c^2). However, on the downside, this has to be balanced against the earth's weaker gravitational attraction, smaller target volume and relatively large source solid angle at the detector.

At present we have focussed our attention on evaluating the rates of WIMP annihilations from the earth's core, since the detector has a much larger acceptance for those events than it does for those coming from the sun. Our analysis has followed closely to that originally outlined by A. Gould [17] for WIMP capture and annihilation from the sun and earth and has been refined and tailored for our detector by G. Liu. [18] In these calculations, we have included the effect of the capture of these WIMPs by the various elements making up the earth's core and their subsequent annihilations into a broad range of fermion-antifermion pairs ($\tau\bar{\tau}, b\bar{b}, c\bar{c}$...). We then take the LUND monte carlo programs coupled with a charged current weak interaction simulator to then evolve from WIMP-WIMP annihilation products to upward going muons in our detector.

The results of this simulation work is shown in Figure 5., where we show a rate of upward going muons for each of five different WIMP candidates modeled. For each of these candidates, we have assumed that the number of WIMPs-antiWIMPs are nearly equal over the mass range of interest and that the WIMP density is sufficient to provide closure of the universe (local DM density of $0.3GeV/cm^3$).

In our first 80 days of operation we have observed a single upward going muon in the detector. This is to be compared with the total downward flux of muons for this period of 2 x 10^5. The event display for this upward going muon event is shown in Figure 6. Taking this single, event we can convert it into a flux measurement of upward going muons to compare with the predictions of the WIMP annihilation fluxes described above. In Figure 5. we have drawn a solid horizontal line corresponding to this upward going muon flux. In addition in this same figure, we show our expected sensitivity for WIMPs after running the full MACRO detector for two years, assuming that we see no additional upward going muon candidates. From the current data, we can see that the MACRO detector can already be used to place limits on some forms of DM candidates. Based on these calculations and measurements we can already rule out muon type sneutrinos and Dirac neutrinos above about $25GeV/c^2$ as major sources of DM. We also see that after several years of operation with the full detector, we will be able to place similar limits on the higgsino contribution to the DM question, while a definitive study of the effects of photinos on the missing matter in the universe will require either longer running or a larger detector.

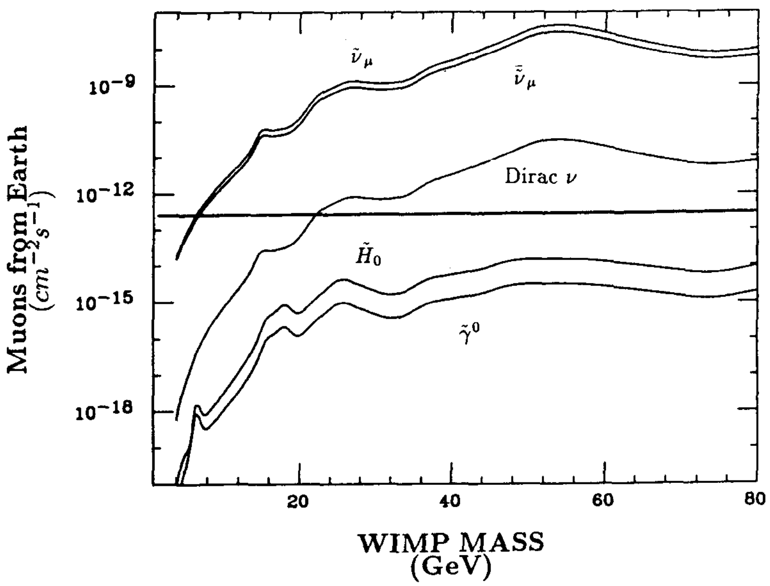

FIGURE 5. The predicted flux of upward going muons due to annihilations of various WIMPs near the center of the Earth. For these calculations, we have assumed that the density of these WIMPs is sufficient to provide $\rho_{WIMP} = \rho_{critical}$ and the energy of the detected muons is greater than 2 GeV. Also displayed is the measured upward going muon flux from the first data taking run of MACRO.

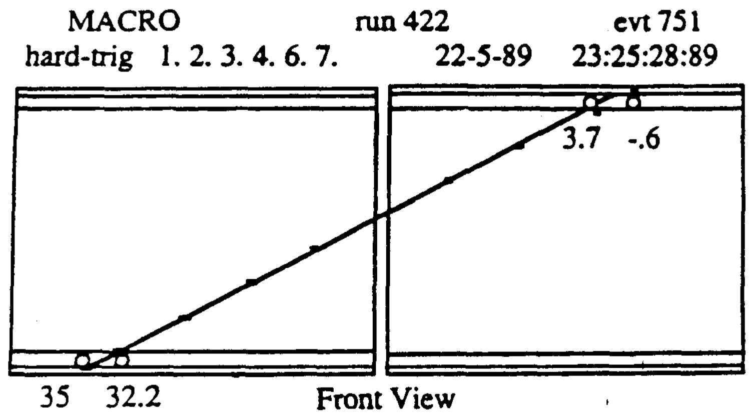

FIGURE 6. MACRO's first upward going muon event. The circles indicate the scintillation counters struck by the muon and the dots correspond to the streamer tube "hits" along its trajectory. The numbers shown are the relative times in nsec with an arbitrary offset of the pulses detected in the given scintillation counter. This particle has an upward velocity of $\beta = 0.995$.

Conclusions

In summary, we have seen that there are a number of very interesting astrophysical, cosmological and particle physics questions awaiting study in the realm of particle astrophysics. We have also seen that by bringing to bear astrophysics, cosmic ray and particle physics techniques and skills to build the next generation of large underground detectors, we are able to address several exciting issues regarding the origin of the universe. It is, of course, our ultimate hope that such research coupled with the work in particle physics and astrophysics independently will eventually lead us to an understanding of the secrets surrounding our universe and its origins and to a real "Theory of Everything".

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