COLD MOLECULAR GAS AS A COMPONENT OF DARK MATTER?

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Abstract. The possibility that the dark matter in galaxies is made of cold, dense clumps of molecular gas is critically discussed from an observational point of view. The various means for detecting such material are examined. While the idea is appealing for various reasons, it is losing ground on the basis of very recent work, although searches for cold molecular gas have triggered a number of new observations which have yielded unexpected results. The only remaining evidences for large amounts of molecular gas concern the central regions of the Andromeda galaxy where it gives only a minor contribution to the total mass, and the external parts of the Small Magellanic Cloud where its contribution might be substantial. Further observational work is needed to obtain a definitive answer.

1. Introduction

It is well known that the rotation of spiral and irregular galaxies gives strong indications for the presence of dark matter in their outer regions. This dark matter can be entirely baryonic provided it does not extend by more than 30-50 kpc from the center (see the paper by Carr in this volume). A widespread opinion is that this matter should be distributed in a more or less spherical halo. However there is no solid proof that this is the case. There are several possibilities for obtaining the shape of the gravitational potential of galaxies, for example the study of polar-ring galaxies (Arnaboldi & Sparke 1994), the use of test objects like globular clusters in our Galaxy for which three-dimensional space velocities are becoming available (Dauphole & Colin 1995), or dynamical tests on disk instabilities (Sparke 1984). However no convincing result has been obtained yet.

Several candidates have been put forward for the dark matter in galaxies. Here I will only discuss one of them: cold molecular gas. This is not a new idea, and it has been proposed sporadically in the past. It is quite natural, as:

- molecular hydrogen which must be the most abundant constituent of this gas is extremely difficult to detect: all its transitions are forbidden due to the symmetry of the molecule, except the electronic transitions which fall in the far-UV and are presently almost inaccessible, including with the Hubble Space Telescope; moreover interstellar dust is extremely efficient at absorbing those wavelengths and makes detection even more difficult;
- molecular hydrogen is very strong against destruction: photodissociation occurs only through lines in the far-UV, and due to the abundance of H_2 these lines become easily optically thick: H_2 shields itself from further photodissociation.

Recently, Pfenniger et al. (1994) and Pfenniger & Combes (1994) have published an extensive theoretical discussion of the possibility that cold molecular gas makes the dark matter of galaxies, not as a spherical halo but rather as an extended disk (however one may conceive that the halo contains substantial amounts of molecular gas left over from the initial star formation: De Paolis et al. 1995). The main arguments of Pfenniger et al. are the following:

- there is a "cosmic conspiracy" between dark and luminous matter which are in relatively constant proportions, while dark matter becomes dynamically important where starlight becomes dim: there seems to be a physical coupling between the two components;
- in the outer disk, dark matter (if in a disk) is roughly distributed like atomic hydrogen as traced by the 21-cm line, and in constant proportion (about 1/30);

- gaseous "halos" (or disks) around galaxies are known to extend very far, from the study of absorption lines in the spectra of quasars;

- the required amount of gas provides a reservoir able to feed star formation for a long time: studies of spiral galaxies show invariably that without such a reservoir, star formation can only proceed for another 1 or 2 Gyr at the rate sustained from 10-15 Gyr, a strange and distressing result;

- large amounts of previously unseen gas seem to be "revealed" in starbursts after merging of two galaxies.

I will now discuss methods to find cold molecular gas in galaxies, first directly then indirectly, and review some results.

2. Detection of cold molecular gas

As discussed before, direct detection of molecular hydrogen is very difficult and must wait for the launch of new satellites: LYMAN in the far-UV, and in a near future the European Infrared Space Observatory (ISO) due for launch in Autumn 1995 or Spring 1996. An attempt at detection of H_2 through observations of its quadrupole 28 µm rotational line in absorption in front of distant infrared sources in the outer Galaxy is programmed with the latter satellite. Another possibility is offered by the detection of the first rotational transition of LiH, a molecule which is expected to co-exist with H_2 as some lithium is formed in the Big Bang; unfortunately this permitted line is at 0.68 µm (444 GHz), a wavelength barely accessible at present with the required sensitivity.

If the gas in question contains heavy elements, there are other possibilities. Actually no one has yet found any pure "primordial" material in the Universe, i.e. a material without heavy elements, and this may indicate that nucleosynthesis by the first generations of stars has already polluted most or all of the existing matter, including the cold molecular gas we are discussing. This gas is thus expected to contain some amounts of heavy elements like O or C, thus molecules like carbon monoxyde CO which is a well-known tracer of molecular gas. CO has its first rotational transition at 2.3 mm wavelength, which is easily excited and has been extensively observed. Still this line is difficult to see if the gas is very cold, not much above the 2.73 K of the microwave background of the Universe. For example, Allen & Lequeux (1993) have found large quantities of molecular gas in the inner regions of the Andromeda Galaxy M 31 which produces only a weak CO emission due to the lack of heating sources. There are absorption marks over the strong stellar light of these regions which are due to dust clouds. As dust is generally well mixed with gas, these marks indicated where to look and this is how we found this gas, whose physical properties have been explored in some detail. A further survey at random positions (Loinard et al. 1995) showed that this cold gas is very widespread and has a mean surface density perpendicular to the disk of M 31 of about 10 M⊙ (solar masses) per square parsec, more than the surface density of the gas in the active, outer regions of star formation of this galaxy. This shows that even if CO is there, it may be difficult to detect if it is too cold.

Observations of CO in absorption in front of the continuum millimeter radiation of radiosources do not suffer from this difficulty, as absorption line intensity is not very sensitive to temperature. Lequeux et al. (1994) detected multiple CO absorptions in front of two extragalactic sources close to the plane of symmetry of the Galaxy, in its outer parts. However their claim that they were seing the cold molecular gas which could make the dark matter in the outer disk is unfounded. Other observations have shown that another molecule, HCO^+, is present in amounts not compatible with cold gas (Lucas & Liszt 1995); it is presently thought that one is rather dealing with a relatively dilute gas which has been processed in shocks or in intermittency regions of the interstellar turbulence (Falgarone et al. 1995). However this does not mean that cold H_2 does not exist. If so, it is probably distributed in small, dense regions of the fractal structure of the interstellar medium which have a small area filling factor, thus the probability that a line of sight encounters such a clump is presumably not high.

There is one tracer which works independently of the geometry and physical state of the gas: gamma rays. Gamma rays are produced by the interaction of cosmic-ray GeV protons or electrons with nuclei of the interstellar matter. Protons produce pions which decay into a pair of gamma photons, and electrons give gamma photons through bremsstrahlung. The first mechanism dominates for gamma rays above 50-100 MeV, and the second below. If the flux of cosmic rays or/and electrons is known, gamma rays trace all the non-stellar matter whatever its density and physical state. The analysis of gamma photons observed with the COS-B satellite by Strong et al. (1988) has shown that if the interstellar gas is mostly atomic in the outer Galaxy the cosmic-ray protons and electrons both have a rather uniform distribution there. There is no independent check for protons but such a check exists for electrons which also radiate radio waves through the synchrotron mechanism in the Galactic magnetic field. Observation shows that the synchrotron emission decreases rapidly at increasing radii; other observations show that this is not due to a decrease of the magnetic field, thus imply a decrease of the flux of electrons, in apparent contradiction with the gamma-ray results. This contradiction disappears if one accepts that there is more gas in the outer Galaxy that mere atomic gas; this implies that there is four times more gas already at 4 kpc from the Sun in the external Galaxy: this is an indication in favor of the existence of abundant molecular gas in the outer Galaxy (Lequeux et al. 1993). However a similar study is under way using data from the GRO satellite, and does not agree with this conclusion (Grenier, private communication): it leaves little room for extra gas in the outer Galaxy.

3. Dust in the external parts of galaxies

As said before, interstellar gas always seems to be mixed with dust, in amounts roughly proportional to the abundance of heavy elements (Bouchet et al. 1985). Thus dust can serve as an indirect tracer of gas. Dust itself can be detected either through its thermal emission (when heated by a radiation field) or through the extinction and reddening it produces on the light of background objects.

Heated dust can thus be seen in the far-infrared or at millimeter wavelengths (see e.g. Guélin et al. 1993 for a map of dust in the edge-on galaxy NGC 891). However if its temperature is only a few K above that of the cosmic background radiation dust cannot be detected in galaxies with the present means; dust associated with cold molecular gas is likely to be cold due to a weak radiation field and to be undetectable in emission.

There is no such problem with extinction or reddening observations, for which temperature is irrelevant. However one should be aware that if the observed medium is clumpy and has only a small area coverage factor, the amount of dust can be considerably underestimated, hence the amount of associated gas. This is probably the case in reality. Moreover optically thick clumps absorb completely the light and do not produce reddening: this is another cause for underestimation of the amount of dust in reddening observations, which are usually easier than extinction observations.

Dust extinction can be observed directly in galaxies by comparing a near-IR image where extinction is small to an image in the visible where it is strong. Dividing a visible image by an infrared one directly yields a qualitative picture of the distribution of dust: see beautiful examples in Block et al. (1994). Unfortunately the brightness in the outer parts of galactic disks or in halos is very faint and detection of dust in these regions is presently difficult, although future efforts with very long exposures will be rewarding. Another difficulty is that dust and stars are not distributed in the same way so that a model for both distributions is necessary in order to interpret the visible/infrared picture quantitatively. A number of recent papers use a statistical approach: measuring the color or spiral galaxies, preferably their visible/infrared color, as a function of their inclination (see e.g. Boselli & Gavazzi 1994): more inclined galaxies are redder because the amount of dust on the line of sight is higher. However as the light is dominated by the inner regions of galaxies this provides no information on the outer regions (disk or halo) which are of interest here.

Another possibility to determine extinction is to count background galaxies through the observed, foreground galaxy. Apparently this has only be done today for the Small Magellanic Cloud (SMC). The results of these already old observations are of high interest: the outer regions of the SMC exhibit an unexpectedly strong extinction, due to clouds 100 pc or so in size (Hodge 1974; MacGillivray 1975; for a discussion and other arguments in favor of cold molecular gas in the SMC see Lequeux 1994). Mac Gillivray explicitly suggested that these dark clouds may contain large amounts of molecular hydrogen. Unfortunately it is difficult to tell how much, as the heavy-element abundances are unknown at these locations.

In the same vein, it is interesting to mention that several authors have found an anticorrelation between the distributions of quasars and galaxies on the sky, that they interpret as due to extinction in the galaxies, which are closer than the quasars. Boyle et al. (1988) find no effect for isolated galaxies but a noticeable effect for galaxies in clusters, implying a mass of dust of at least 10^{10} M$\odot$ per cluster thus $10^{12.3-13}$ M$\odot$ of gas. This gas mass is not larger, or is even smaller than the mass of hot gas in clusters revealed by X-ray observations but it is a strong lower limit as the medium can be clumpy and as dust is possibly destroyed in this hot gas. More recently, Romani & Maoz (1992) find a quasar-large cluster anticorrelation up to large radii (1°!), implying masses of dust of some 3 10^{12} M$\odot$ per cluster and then masses of gas of some $10^{14-14.7}$ M$\odot$, a substantial fraction of the dark matter implied by the dynamics of clusters. Fall & Pei (1993) find strong statistical evidence for dust extinction in the damped Lyman α absorption-line systems in front of quasars, which are supposed to correspond to disks of galaxies, implying limits to the contribution of gas to the mass density of the Universe of $10^{-3} \leq h\Omega_{gas} \leq 3\ 10^{-2}$. The range of possible values is unfortunately large although the upper limit is comparable to the upper limit for baryonic matter. Searches for absorption lines of molecular hydrogen in the spectra of quasars have not been conclusive except in a single case, but this may be due to the probably clumpy distribution of H_2, which may be clumpier than that of the dust and of the rest of the gas.

A potentially very powerful, although difficult method is to look at the reddening of background galaxies behind the disk and/or halo of a nearby galaxy. If sufficiently faint levels can be reached, background galaxies are very numerous while they can still be distinguished from stars, and this number compensates to some extent for the intrinsic dispersion in their colors. Zaritsky (1994) has applied this idea to the halo of two nearby galaxies. He imaged with a CCD in the blue and in the near-infrared a number of fields at two distances from each of these galaxies, and measured the average color of the background galaxies in each field. The average color of background galaxies at a radius of 60 kpc is redder by 2σ than the average color at a radius of 220 kpc. If the effect is real and assuming that extinction decreases linearly with radius, the mass of dust is 3 10^8 M☉ out to 60 kpc and the corresponding amount of gas probably of the order of 10^{11-12} M☉, enough to make the dark matter. However the approach is fraught with difficulties. The worse one is probably the relative calibration of frames taken in different conditions, while one wants to measure colors to better than 1/100 of magnitude. In order to bypass this problem, we have observed with the Canada-France-Hawaï 3.6-m telescope and a 2048x2048 pixel CCD covering the external regions of one side of the edge-on galaxy NGC 7814 (Lequeux et al. 1995). The infrared/visible (V-I) color of background galaxies between $25<V<27$ magnitude has been measured over the whole frame and their mean color compared near and far of the galaxy. There are about 25 usable galaxies per square arc minute, but as the dispersion in their intrinsic colors is large we found no effect $\geq 2.4\sigma$ except in the outer disk, where we find a dust-to-atomic gas ratio comparable to that in our Galaxy near the Sun. On the other hand, we have found an unexpected redder color in the outer parts of this galaxy, which cannot be due to reddening by dust but suggest the existence of very abundant very-low mass ($\approx$0.3 M☉) stars which may make the required dark matter!). Clearly one must repeat this observation on other galaxies. We are planning such observations in the immediate future.

4. Conclusion

We have discussed the possibility that cold molecular gas makes at least a part of the dark matter in spiral and irregular galaxies. In spite of many efforts, the evidence for this is rather fragmentary and less encouraging that it was some time ago. A multi-means approach is probably the best one to solve this difficult, but challenging problem. Extinction or reddening observations of background objects appear particularly interesting. A search for events ***in absorption*** in the EROS-MACHO-OGLE programs might turn out to be very rewarding as it offers a simple way to discover small, dense fragments of interstellar matter in the disk or in the halo of our Galaxy which are expected to contain cold molecular gas. As interstellar matter is known to have scales as small as one astronomical unit (the radius of the Earth's orbit) the time scale for such events might be of the same order as that of the microlensing events. Chromatism (extinction is stronger in the blue than in the red) would be a characteristic signature of such extinction events if absorption is not saturated.

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