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DUST AND GAS IN THE OUTER PARTS OF GALAXIES

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1. Abstract

We review the observations of dust in the outer disks and the halos of spiral and irregular galaxies. These observations not only yield the abundance of dust and indirectly of heavy elements, but also give indirect information on molecular hydrogen which has been proposed as a constituent of dark matter in galactic disks. Dust can be detected either through its thermal emission or through the reddening and extinction it produces on the light of background objects. Detection of the thermal emission of dust at millimeter wavelengths using bolometers on large telescopes is making considerable progress and we are close to the point where dust will be seen in this way out to the 25-26th mag. arcsec^2 blue isophote of the disk. Dust has now been detected in these outer regions of the disks from a statistics of the colors of disks as a function of their inclination, and by direct measurements of the reddening of background galaxies. New results concerning M 31 are presented. There is a surprisingly high dust/gas ratio, and also massive star formation, at these very large galactic radii. The evidence for dust in galactic halos is uncertain.

2. Introduction

Due to relatively small column densities and low temperatures it is difficult to detect molecular gas and dust in the outer parts of galaxies. However there are strong incentives to this detection. There have been suggestions for

large amounts of cold molecular hydrogen in the external parts of galactic disks and even in galactic halos (Lequeux et al. 1993; Pfenniger et al. 1994; de Paolis et al. 1995). It is almost impossible to detect such molecular gas directly except through the UV absorption lines produced by galactic disks in front of quasars, which might be detectable with the HST at redshifts larger than 0.07. In spite of much effort, only HI has been detected to radii as large as 70 kpc in big spirals, but no H_2 (e.g. Lanzetta et al. 1995). The only case where H_2 has been detected remains that of an absorption system at z=2.77 in front of the quasar PKS 0528-250 (Foltz et al. 1988). If this molecular gas is cold, the usual tracer, the CO molecule, may not be sufficiently excited to produce millimeter line emission. CO can be detected in absorption, but only if the few available lines of sight to sufficiently strong millimeter continuum sources intercept molecular clouds. The CO absorptions detected by Lequeux et al. (1993) and Lucas & Liszt (1996 and references herein) are no more attributed to a cold, dense molecular gas but rather to a low-density, warm interstellar gas (see e.g. Falgarone et al. 1995 and de Geus, this conference). The idea of large amounts of diffuse molecular gas in the outer parts and in the halos of galaxies has received another serious blow from the Galactic gamma-ray measurements with EGRET on board the Gamma Ray Observatory (Digel et al. 1996; Salati et al. 1996). The possibility that the molecular gas is in dense clumps partially opaque to cosmic rays and gamma rays remains open, however (F. Combes, this conference).

It is however easier to detect dust through its thermal emission and through the extinction and reddening it produces on the light of background objects. As dust seems to be always associated with gas, the detection of dust without HI 21-cm emission might indicate indirectly the presence of relatively diffuse molecular gas. When dust is observed to correlate with HI, it is possible to determine the dust/gas ratio and indirectly the metallicity of the gas as the dust/gas ratio is proportional to metallicity (Bouchet et al. 1985); this may offer the best way to determine the metallicity in the outer regions of galactic disks. In this review, we will concentrate on the detection of dust in the outer disks and halos of spiral and irregular galaxies. Section 3 deals with observations of the thermal emission of this dust and Section 4 with observations of extinction and reddening of background objects. Section 5 contains a discussion with reference to dust in objects at cosmological distances, and conclusions.

3. Thermal emission of dust in the outer parts of galaxies

IRAS has opened the possibility of observing systematically the thermal emission of interstellar dust. However its spectral range was limited to 100

μm on the long-wavelength side, making it impossible to detect cold dust. ISO, with its limitation at 200 μm, will do better but might still be relatively insensitive to the cold dust which could be present in the outskirts of galaxies where the radiation field is weak. It is necessary to observe at longer wavelengths for obtaining a good determination of the column density of dust. COBE has made such observations for our Galaxy; unfortunately our location in the galactic plane is such that the emission by the cold dust in the outer disk or in the halo cannot be easily distinguished from that of local, warmer dust. There are a few observations of submillimeter extragalactic dust emission done with the Kuiper Airborne Observatory, but this facility is now closed. SOFIA and/or FIRST will allow observations of cold dust in the outer parts of external galaxies. But the advances in millimeter bolometer arrays associated with large radio telescopes, such as the MPIfR 1.2-mm 19-channel bolometer array on the IRAM 30-m telescope, make it already possible to detect dust emission at large galactic radii with a good angular resolution.

The best example is that of NGC 4565 (Neininger et al. 1996; see also Neininger, this conference), an edge-on spiral in which dust emission at 1.2 mm has been seen as far as 19 kpc from the center (assuming a distance of 10 Mpc), i.e. at much larger radii than the CO emission. The dust emission from the outer regions correlates well with the 21-cm line emission and obviously arises from HI clouds; it shows the same out-of-plane warp as HI. Its detection offers an unique opportunity to derive the dust absorption cross section per H atom, $\tau_\lambda/N(H)=5\ 10^{-27}$ cm^2 for λ=1.2 mm at 10-12 kpc from the center; this parameter is difficult to measure in the Milky way due to distance ambiguities. In NGC 4565, it is very close to that predicted by Draine & Lee (1984) for local diffuse clouds. Observations in progress for NGC 891 and NGC 3079 (Zykla et al., Braine et al. in preparation) seem to point to similar values.

How much farther can we hope to detect thermal emission from dust? Taking the example of NGC 4565 (data from van der Kruit & Searle 1981) and assuming that the interstellar radiation field scales with the surface brightness and that the grain properties are constant, we estimate a dust temperature of 9 K at the optical and HI cut-off radius of 24-25 kpc, corresponding to a surface brightness μ_J = 26.5 mag. arcsec^{-2} in the J band of van der Kruit & Searle. The dust emissivity per H atom becomes there 2.3 times weaker than the value given above for R=12 kpc. With the 30-m telescope the present sensitivity is about 1 mJy per 12" beam at 1.2 mm; for dust at 9 K, this corresponds to N(HI) $(Z/Z_\odot)^{-1}$=4 10^{21} cm^{-2}, assuming that the abundance of dust is proportional to metallicity Z. This would make it possible to detect the dust emission at 24 kpc in NGC 4565 if the abundance of dust and heavy elements was like near the Sun. The abun-

dance is likely to be smaller by a factor of a few (see later the discussion of M 31), but we are not far from the goal. The extension of the MPIfR bolometer to 37 channels, this winter, may make a detection within reach. The situation is similar for NGC 891.

Going to shorter wavelengths increases the intensity of the dust emission, which scales as $\lambda^{-(3.5-4)}$ in the submillimeter domain. The 99-channel SCUBA bolometer, which will be installed soon on the JCMT, will operate down to 350 micrometers, near the peak of the dust emission, and may allow to detect very low dust column densities; however the dust emission varies as T_d^5 at this wavelength and is hard to interpret. Moreover the atmosphere becomes nearly opaque making sensitive observations difficult.

The ISO satellite has a poor angular resolution at long wavelengths and, as noted above, may miss the bulk of cold dust. However the dust emission is not uniform and due to the existence of hot stars in the outskirts of galaxies (see later for M 31) there might be warm dust there. This will probably make possible a detection at 200 μm, to a limiting column density perhaps an order of magnitude better than at 1.2 mm. Such observations are planned. The observational limit will probably arise from confusion with Galactic cirruses.

4. Extinction and reddening by dust in the outer parts of galaxies

For the time being, it seems somewhat easier to detect dust in the outskirts of galaxies through extinction and/or reddening of the light of background objects than through its thermal emission. We will discuss the results obtained up to now: first by a statistics of surface brightnesses and colors of galaxies as a function of their inclination, then by observation of individual foreground objects.

4.1. STATISTICAL EXTINCTION IN GALAXIES OF VARIOUS INCLINATIONS

The analysis of surface photometry of galaxies as a function of inclination has shown that spiral galaxies, in particular Sb and Sc ones, suffer from considerable extinction at least in their central regions. But there is a controversy as to the quantitative amount of extinction, which is apparently due in part to selection effects in the galaxy samples (see e.g. Valentijn 1994). The basic idea in such studies is that inclined galaxies should have a lower surface brightness and be redder than face-on galaxies due to extinction by their internal dust. A simple, useful parameter to characterize extinction is the quantity C such that: μ(obs) = μ(face-on) - 2.5 C log(a/b) where μ is the surface brightness in a magnitude scale and a/b is the observed axis ratio. For a simple slab model, C is equal to unity for a trans-

parent galaxy and to zero for an opaque one. The physical interpretation of C depends obviously of the respective distribution of the stars and dust. After a thorough discussion, Valentijn (1994) concludes that Sb galaxies and high-surface brightness Sc and Sd galaxies have low C values (high extinction) over the whole of their disks, at least on the average as dust can be distributed very irregularly. C is still found of the order of 0.2-0.5 in the blue at their μ_B=26 mag. arcsec^{-2} isophote while the fainter surface brightness Sc and Sd galaxies are nearly transparent (C = 0.5-0.7 in the blue) at their μ_B=26 mag. arcsec^{-2} isophote. Peletier et al. (1995) have recently given a discussion of the B-K color of galaxies as a function of inclination. This color is a good indicator of the amount of extinction (plus scattering!) since light in the K band is much less affected by dust than light in the B band. They find that while extinction is generally large (but variable from galaxy to galaxy) in the central regions, it is usually small in the outer parts, i.e. at μ_K=21 mag. arcsec^{-2} corresponding roughly to μ_B=25 mag. arcsec^{-2}. The actual figures depend on the respective distribution of dust and stars, and there is a large range of acceptable solutions for the relative scale lengths (in the disk) and scale heights (perpendicular to the disk) of dust and stars. For our purpose, we will extract from this study a maximum amount of extinction normal to the disk at μ_B=25 mag. arcsec^{-2} of A_B = 0.1 to 0.4. This conclusion is in agreement with that of Giovanelli et al. (1994) who find that extinction is small at μ_I=23.5 mag. arcsec^{-2}, about the same level. To conclude, it appears that extinction is small, but not necessarily negligible, in the outer parts of the disks of galaxies.

4.2. DIRECT DETERMINATION OF REDDENING OR EXTINCTION IN THE OUTER DISKS

4.2.1. *NGC 7814*

In a few cases, extinction in the outer disks can be seen directly. This is the case in the warped edge-on Sa galaxy NGC 7814, for which Lequeux et al. (1995) have obtained very deep images in V and I. These images reveal clearly the torsion of the disk and dust absorption marks out to 238" radius (17.5 kpc for an adopted distance of 15 Mpc), almost as far as the outermost extent of the visible disk (264" or 19.4 kpc). There are a few background galaxies seen behind the absorption marks at an average radius of 14 kpc, with a 2.4σ average color excess E(V-I)=0.10 mag. with respect to the galaxies in blank surrounding fields. Assuming a Galactic extinction law this corresponds to A_B=0.7 mag., then given the inclination of the warped disk at this location to a face-on extinction of A_B=0.2 mag., well within the range indicated by the statistical studies mentioned above. As the column density of HI is known at this location, one can determine the N(H)/E(B-V) ratio which is of the order of 5 10^{21} cm^{-2} mag.$^{-1}$, of

the same order as the ratio near the Sun in our Galaxy. This suggests that the metallicity is still high at this radius. Unfortunately the measurement of extinction is only at 2.4σ, and it is not easy to determine the surface brightness of the disk at this location because of the difficulty in separating it from the enormous bulge of the galaxy; examination of fig. 6 of van der Kruit & Searle (1982) suggests μ_B=25.5 mag. arcsec^{-2}.

4.2.2. *Overlapping galaxies*

When two galaxies are on the same line of sight, it is possible to obtain information on the extinction in the foreground galaxy after some interpolation of the surface brightness of the background galaxy is made. Some examples have been presented by J. Frogel and R.E. White at this conference, with the result that extinction is only a few tens of magnitudes in the external regions. To this study one should add that by Andreakis & van der Kruit (1992). They have studied the extinction by the spiral galaxy NGC 450 on the background spiral UGC 807, whose center projects behind the μ_B=25 mag. cm^{-2} isophote of NGC 450. The maximum extinction allowed for by the data is A_B=0.3 mag., also compatible with the studies just cited.

4.2.3. *The Andromeda galaxy M 31*

Very recently J.-C. Cuillandre, Y. Mellier, B. Fort, R.J. Allen and J. Lequeux (in preparation) have succeeded in detecting the extinction in the outermost regions of the Andromeda galaxy M 31 by studying statistically the color of background galaxies. They observed with a 8192×8192 pixel CCD mosaic at the prime focus of the Canada-France-Hawaii 3.6-m telescope, kindly loaned by G. Luppino (University of Hawaii). The mosaic covered a field 28'×28' whose center is located at 116'=23.2 kpc from the center of M31 on the SW side of the major axis. This region is at the extreme limit of the visible disk of the galaxy (Innanen et al. 1982, Walterbos & Kennicutt 1988) and of the distribution of neutral hydrogen (Newton & Emerson 1977). The B surface brightness there is approximately μ_B=26 mag. arcsec^{-2} (Walterbos & Kennicutt 1988). The cumulative exposure times were 4 hours in the V and in the I filters, with photometric quality, and the image quality on the resulting, combined frames is about 0.8" in both bands. An algorithm was used to separate stellar images from the images of galaxies and was quite successful in spite of the crowding of the frames, except for regions around bright objects or groups of objects. A map of the mean V-I color of the galaxies with I magnitudes between 22 and 28 was then constructed. The difference with the average V-I in a reference region believed to be free of extinction by M 31 gives the color excess due to the dust of M 31. This map is shown on fig. 1. It correlates well with the HI map of Newton & Emerson (1977) corrected for the primary beam

response.

From the data of fig. 1, and assuming that the extinction law in the visible is similar for this region of M 31 and for the Solar neighborhood (a reasonable assumption according to the study of extinction in the Magellanic Clouds by Bouchet et al. 1985), the dust-to-gas ratio is found to be 0.4 times that in the Solar Neighborhood. This is a provisional value which will be refined by a more detailed study. It shows that at this large radius the gas of M 31 still contains a large amount of dust indicative of an unexpectedly large metallicity, about 0.4 solar. An alternative would be to imagine that the studied region contains not only atomic, but also molecular hydrogen with a distribution similar to that of HI, and that the dust corresponds to both components; the dust/gas ratio and the metallicity would be reduced accordingly. This molecular gas should however have a large surface filling factor in order to produce a sufficient average extinction on background galaxies, and is not the gas distributed in dense, high-density small clumps advocated by Pfenniger et al. (1994). The discussion in the introduction of this paper does not favor the existence of diffuse molecular hydrogen and we assume that the column density of H_2 is negligible. The average color excess in the most reddened region, inside the N(H)=1.28 10^{21} atom cm^{-2} contour of fig. 1, is E(V-I)=0.18 mag., corresponding to A_B=0.4 mag.

During the reduction of the M 31 frames, stars were separated from galaxies. We noticed that the mean V-I of stars is smaller (bluer) in some regions corresponding roughly to the peaks of HI. We thus obtained color-magnitude (CM) diagrams of these stars. They are displayed on fig. 2. In a reference region with low gas column densities (the CCD at the SW of the image; right panel) one sees a red giant branch, an horizontal branch at V=25.5, and a loosely populated AGB branch. There are not many stars outside these features, showing that contamination by Galactic stars is rather small. We have checked that the contamination by galaxies is also not large. The left panel displays the CM diagram for stars in the "blue" regions. The contamination and photometric errors are somewhat larger here due to to a higher density of objects, but the giant branch and the AGB branch are still well visible. The differences between the two CM diagrams are due to different populations (mainly halo stars in the reference field and a mixture of halo and disk stars in the other field), but this has to be studied in details. These CM diagrams resemble closely some diagrams obtained on the halo of M 31 with the HST and presented by M. Rich at this conference. The most interesting feature for our present purpose is the presence in the left diagram of blue stars with V-I around 0.0, as a vertical sequence well separated from the red giant branch. These are main-sequence B1-B9 stars. Thus there is still massive-star formation in this remote part of M 31! Figure 3 is a map of the ratio of blue to red

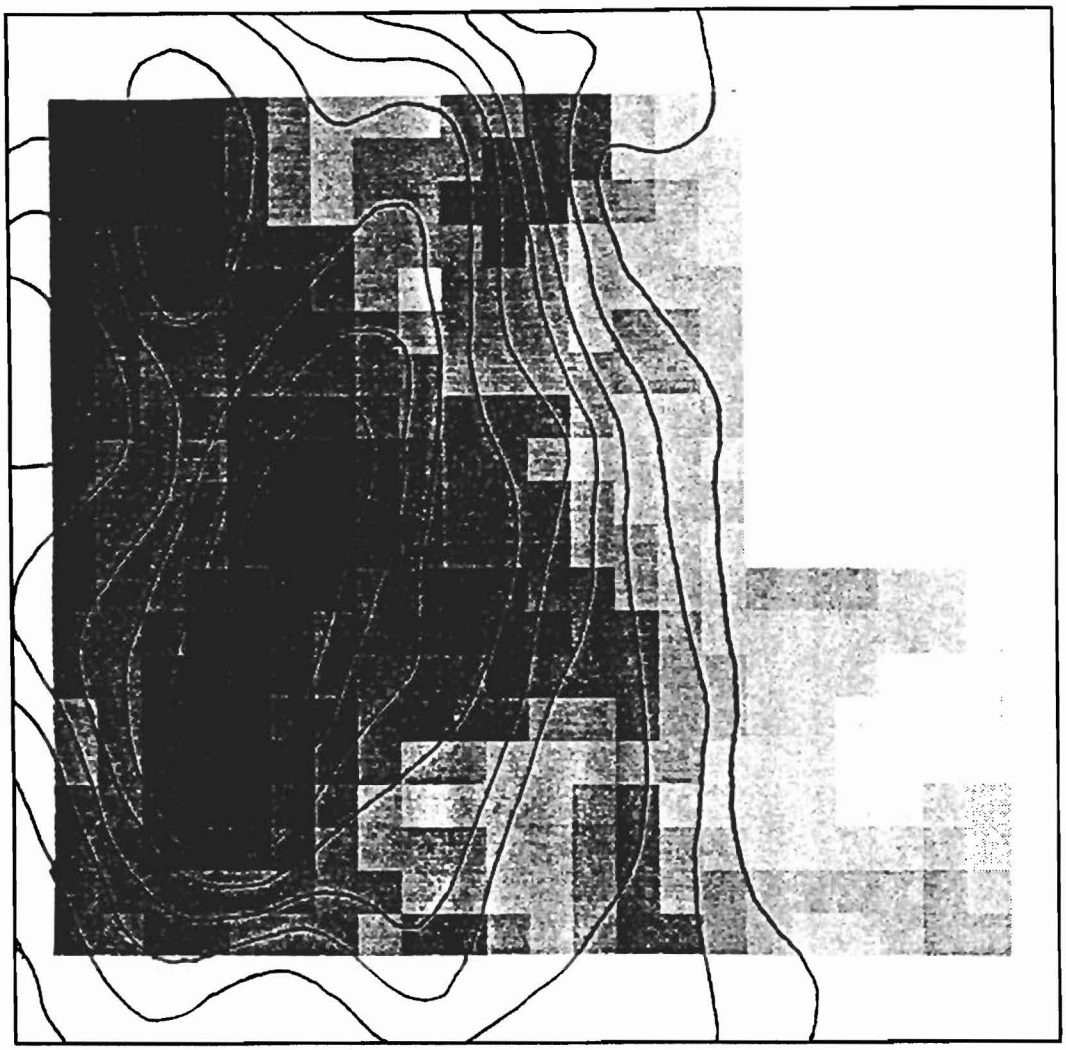

Figure 1. Map of the mean V-I color of background galaxies in a field at the extreme SW of M 31 (grey scale), compared to the column density of atomic hydrogen (contours). The field center is at $\alpha(1950)$=00h 33m 21.4s, $\delta(1950)$=+39° 32' 21". The color data are smoothed to roughly the same resolution as the HI data (3' EW × 5' NS), resulting in the loss of the outer part of the image. The size of the outer square is 28'×28' (5.6×5.6 kpc^2). North to the top, east to the left. The part of the image at the upper right was lost due to the guiding probe. The grey scale goes from V-I=0.74 (white) to 1.06 (darkest), on a linear scale. The HI contours correspond to column densities of (1...9) × 1.6 10^{20} atom cm^{-2}. Note the correlation between the reddening of background galaxies and the column density of atomic hydrogen.

stars over the whole studied field, at the same angular resolution as fig. 1. It gives a first approximation to the relative rate of massive star formation. The correlation with HI is obvious, although less good as for the reddening. An earlier study of the CM diagram of stars in a region located near the middle of the left side of our field (Richer et al. 1990) missed the blue stars which are almost absent in this area. However Hodge et al. (1988) and Davidge (1993) found blue stars in two different fields located at 20 kpc from the center of M 31.

Through a careful study of the effects of contamination on star density and photometry, it will be possible to obtain more information, in particular the luminosity and mass functions of the B stars, and the mean metallicity and metallicity dispersion of the background of older stars through the morphology of the horizontal, giant and AGB branchs. Already a comparison of the HR diagram of the comparison (halo) field with those of globular clusters suggests a metallicity comparable to that of 47 Tuc, [Fe/H]=-0.7.

4.2.4. *The Small Magellanic Cloud*

It is also possible in principle, although considerably more dangerous given the existence of large-scale structures in the distribution of galaxies and the difficulties of calibration, to use counts of background galaxies instead of colors to map extinction. In this way, large amounts of extinction have been suggested around the Small Magellanic Cloud with no correlation with the distribution of HI thus suggesting the presence of large amounts of molecular hydrogen (see a discussion in Lequeux 1994). However given our experience we are now somewhat suspicious about these results, which require confirmation through a statistical study of the colors of background galaxies now undertaken by P. Hodge using archival HST data.

4.3. DUST IN THE HALOS OF GALAXIES

Until now, we have only discussed dust in the disk of spiral galaxies, but the presence of dust has also been suggested in their halos. Zaritsky (1994) has compared the average B-I color of background galaxies at a projected radius of 60 kpc around two spiral galaxies (NGC 2835 and NGC 3521) with that at a radius of 220 kpc, and found that the former are redder by 0.067 mag. with respect to the latter, a 2σ effect. If real, this detection has profound consequences as it would correspond to a total mass of dust of 3 10^8 $M_\odot$ within 60 kpc and a corresponding mass of gas of more than 3 $10^{10}(Z/Z_\odot)^{-1}$ $M_\odot$, Z being the metallicity, assuming that gas and dust are well mixed. This would open the possibility that the dark halo is made of such material. Unfortunately these measurements had to be performed with different exposures at different times, with considerable difficulties

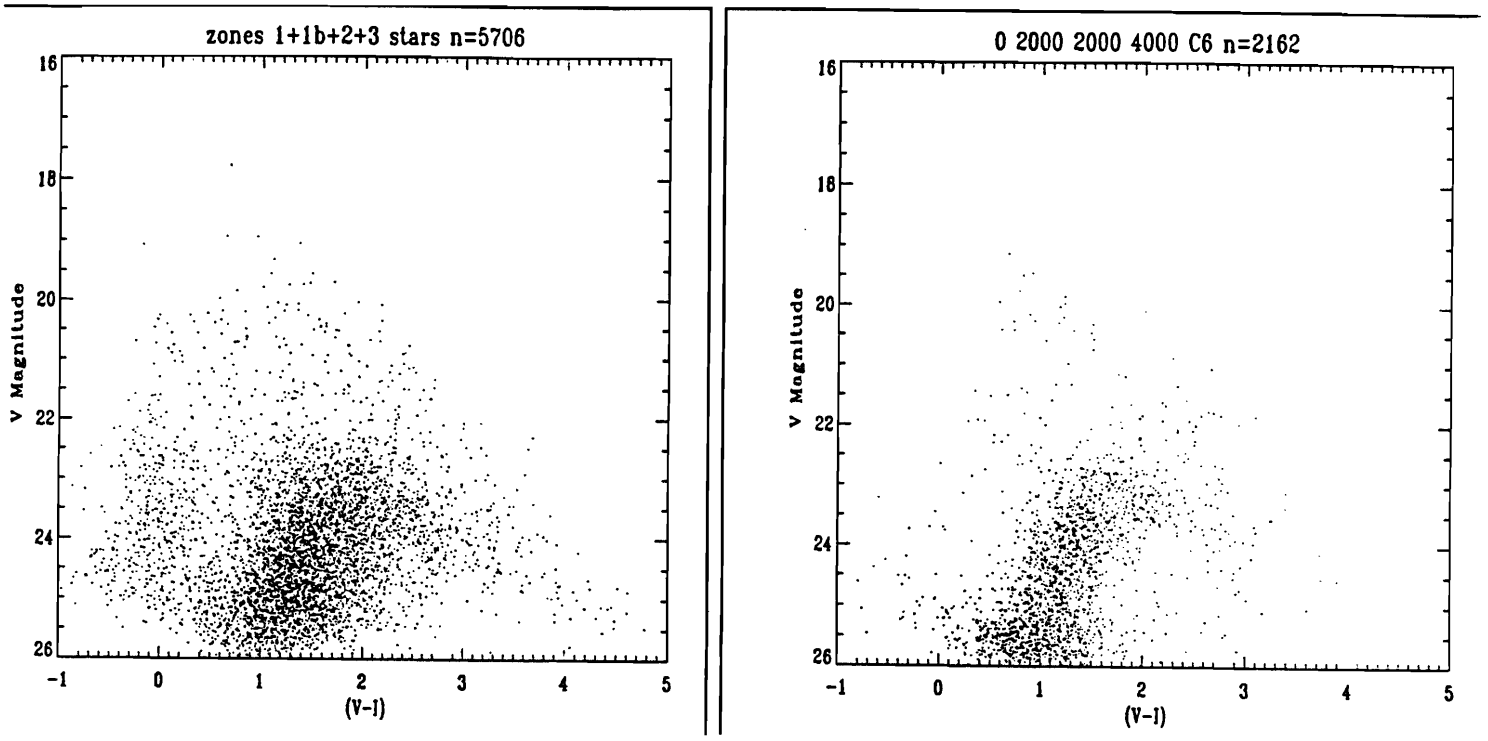

Figure 2. V vs V-I color-magnitude diagrams for stars in a region of the outskirts of M 31 without detected atomic hydrogen (right) and with a large column density of atomic hydrogen (left). The diagram on the right shows a giant branch, the beginning of an AGB and an horisontal branch at V=25.5 mag. (M_V=1.0 mag.). Contamination by galactic stars and background galaxies is small, and the vast majority of the stars belong to M 31, probably to its halo. The number of stars is indicated above. The diagram on the left shows the same features but with conspicuous differences, probably due to a disk population. There is also a vertical sequence of blue stars around V-I=0.0, which is absent on the other diagram.

in cross-calibrating the different frames. Recently, Lequeux et al. (1995) have done a similar work in the range of distances 15 kpc to 35 kpc from the center of NGC 7814 (outside the disk) and found no gradient, and no variations in the mean V-I colors of background galaxies within 4.4 x 4.4 kpc^2 squares covering the field, within 2.4 times a rms deviation of 0.04 mag. This corresponds approximately to the same accuracy as quoted by Zaritsky (1994), but the result is considerably more secure as it was obtained with a single CCD covering all the field. Lequeux, Fort, Dantel-Fort, Cuillandre and Mellier (in preparation) have done a similar study around NGC 5907, an edge-on galaxy, and similarly found no color gradient for the background galaxies. A provisional value for the difference in the mean V-I of galaxies

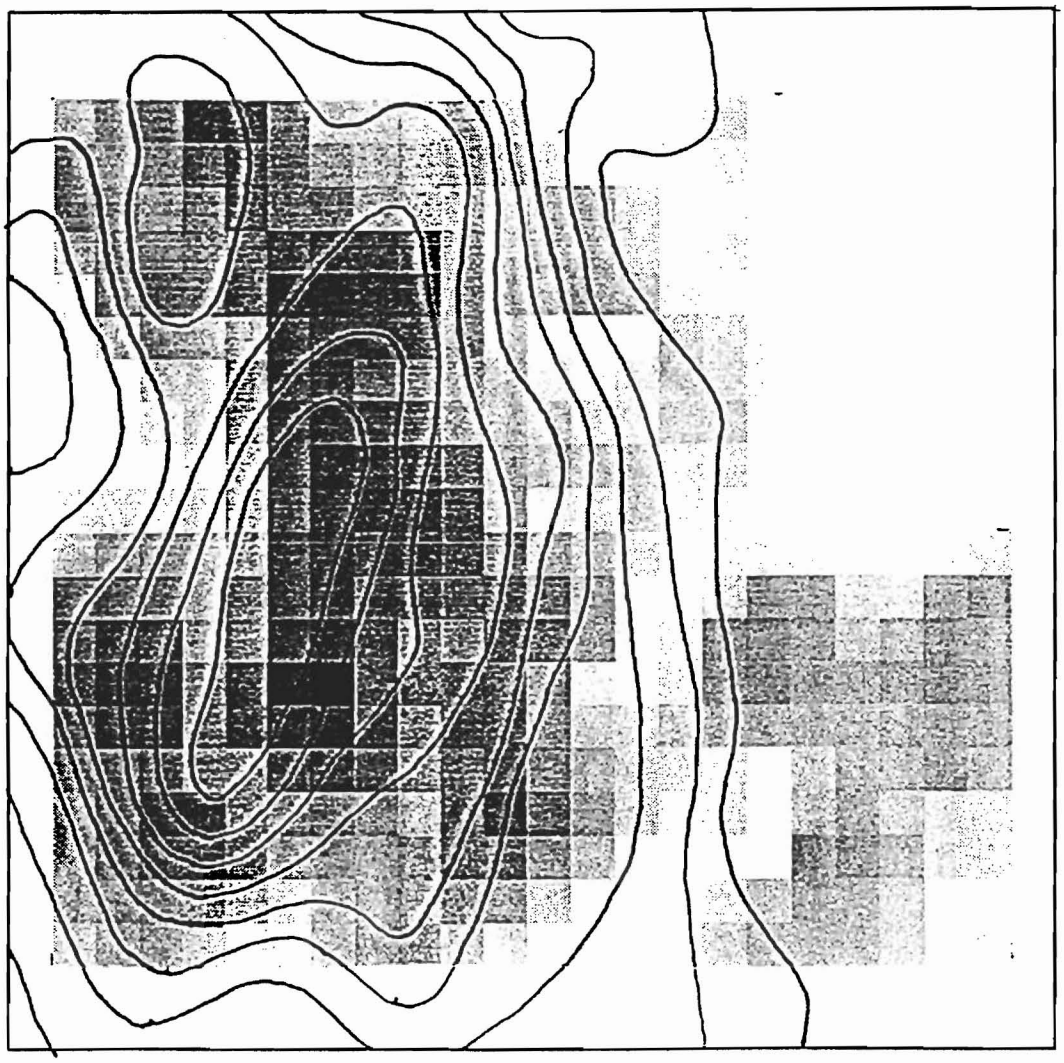

Figure 3. **Grey-scale map of the ratio of blue to red stars in the observed region of the outskirts of M 31. The blue stars are defined as having V-I≤0.4. The darker areas have more blue stars. The contours represent the column density of atomic hydrogen, as for fig. 1. Note the general correlation between the two patterns, but also the shift of the maxima with respect to each other.**

between a long strip located between 2.7 and 5.5 kpc parallel to the major axis and a more distant reference region is Δ(V-I)=-0.03±0.04 mag.; this can certainly be refined by further analysis. This observation was made

with MOCAM, an array of 4 2048×2048 pixel CCDs at the prime focus of the Canada-France-Hawaii Telescope, also covering the whole field at once. In conclusion, the evidence for dust in the halos of spiral galaxies is weak, but the limits are not yet sensitive enough to give stringent constraints on gas as a constituent of the dark halos.

5. Discussion and conclusions

We have shown that there are good evidences for a substantial amount of dust in the outermost regions of the disks of spiral galaxies. The typical extinction through a face-on disk is of the order of 0.2 mag. in the blue at a surface brightness μ_B=26 mag. arcsec^{-1}. For M 31, the only galaxy for which this information is available, the extinction correlates well with the column density of atomic hydrogen. This does not leave much room for molecular hydrogen unless it has a distribution similar to that of HI or is distributed in dense clumps covering a small fraction of the surface. If we neglect molecular hydrogen, the dust/gas ratio is given by the ratio of extinction to HI column density and can be calibrated on the Galactic ratio near the Sun if the dust has optical properties not too different from the Galactic dust. For NGC 7814 the dust/gas ratio (uncertain) is approximately like near the Sun at a radius of 14 kpc, and for M 31 where it is better determined it is approximately 0.4 of that near the Sun at 22 kpc radius. This implies in turn surprisingly large values of the metallicity at such large radii. These high values were not completely unexpected, however. Jacoby & Ford (1986) have measured an oxygen abundance O/H = 3.2 10^{-4} in an HII region 17 kpc from the center of M 31, and of 1.2 10^{-4} in a planetary nebula at 33 kpc projected radius (however an object with halo kinematics), in rough agreement with the present determination. In our Galaxy, de Geus et al. (1993) and Digel et al. (1994) have found a cloud with CO emission, hence heavy elements, associated with an HII region at a kinematic distance of 28 kpc, almost at the edge of the HI disk whose kinematic radius is of the order of 30 kpc.

Recent abundance measurements in the outer Galaxy indicate a surprisingly small abundance gradient (Kaufer et al. 1994), in qualitative agreement with the above findings. It is not yet clear if the formation of massive stars found at large radii at least in M 31 and in our Galaxy is sufficient to account for the observed heavy elements, or if one has to invoke radial mixing or preferential infall in the inner disk of spiral galaxies.

In general, formation of heavy elements and of dust appears to have occured early in the evolution of the Universe. The metallicity is of the order of 1/10 $Z_\odot$ in damped Lyman α absorption systems at z between 1.7 and 3, with a stronger depletion of chromium which is believed to indicate

the formation of dust (Pettini et al. 1994). The dust abundance predicted in this way (also 1/10 of near the Sun) is found directly through a reddening of background quasars (Pei et al. 1991). This has been discussed by M. Fall at this conference. Although it is yet not possible to clearly relate the damped Lyman α systems to the present galaxies, this shows that relatively high abundances in the gas and large amounts of dust existed in the material from which galaxies are formed. But we still have to understand how heavy-element abundances and dust/gas ratios not much smaller than near the Sun have been built in the outskirts of spiral galaxies.

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