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# Dust and star formation in the outermost parts of M 31<sup>\*</sup>

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**Abstract.** We have obtained deep CCD images in V and I of a  $28' \times 28'$  field in the extreme outskirts of M 31, at 23 kpc from the center. We detected the reddening of background galaxies produced by dust in M 31, and found a good correlation between reddening and the column density of H I. This does not favor the presence of diffuse molecular gas in the outer disk of the galaxy unless it has substantially the same distribution as the H I. The dust-to-gas ratio is about 0.5 times that in the solar neighbourhood. We also obtained deep color-magnitude diagrams for the stars of M 31. We derive for the halo stars a metallicity of about 1/4 of solar. Surprisingly, massive star formation is still active near the extreme limit of the disk.

**Key words:** galaxies: M 31 - galaxies: ISM - galaxies: stellar content - galaxies: halos - galaxies: abundances

## 1. Introduction

Because of relatively small column densities and low temperatures due to a small radiation field, it is difficult to detect molecular gas and dust in the outer parts of galaxies. However there are strong incentives to this detection. Direct detection of molecular hydrogen is almost impossible, and CO is a poor tracer in these regions because it may not be warm enough to emit reasonably strong millimeter lines. It should however be possible to detect dust through the extinction and reddening it produces on the light of background objects. As dust appears to be always associated with gas, the detection of dust without H I 21-cm emission might indicate indirectly the presence of relatively diffuse molecular gas. When dust is observed to correlate with H I, one can 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 Letter, we will present a new method to detect dust in the outer parts of galaxies, based on the observation of the reddening of distant background galaxies. Section 2 describes the method and its application to the outer disk of M 31. Section 3 presents color-magnitude diagrams for the stars of M 31 which show in particular the existence of young, high-mass stars in the outer disk. A map of the recent star formation is presented in Section 4. Section 5 contains the conclusions and perspectives for future work.

## 2. Extinction in the outermost disk of the Andromeda galaxy M 31

We observed at the prime focus of the Canada-France-Hawaii telescope a  $28' \times 28'$  field centered  $116' = 23.2$  kpc from the center of M 31. This region is at the extreme limit of the visible disk of the galaxy on the SW side, the B surface brightness being approximately  $\mu_B = 26$  mag.arcsec<sup>-2</sup> (Innanen et al. 1982; Walterbos & Kenicutt 1988). It also includes the outer boundary of the H I disk as observed by Newton & Emerson (1977). The observations were made with a  $8192 \times 8192$  pixels CCD mosaic (Metzger et al. 1996), kindly loaned by G. Luppino. The observation nights were photometric.  $12 \times 20$ -minute exposures were obtained with a V filter, and the same with a I filter giving a response close to the Cousins system. The individual frames were slightly shifted with respect with each other, then recentered and the median was taken for each pixel, efficiently eliminating bad pixels affected by the impact of cosmic rays. The cumulative exposure times were thus 4 hours with each of the filters. The image quality on the combined frames is about  $0.8''$  in both bands. Each of the eight  $4096 \times 2048$  pixel CCDs of the mosaic was separately calibrated using standard stars of the SA 113 Landolt (1992) field. These stars span a reasonable range in color, so that color equations can be computed. Each

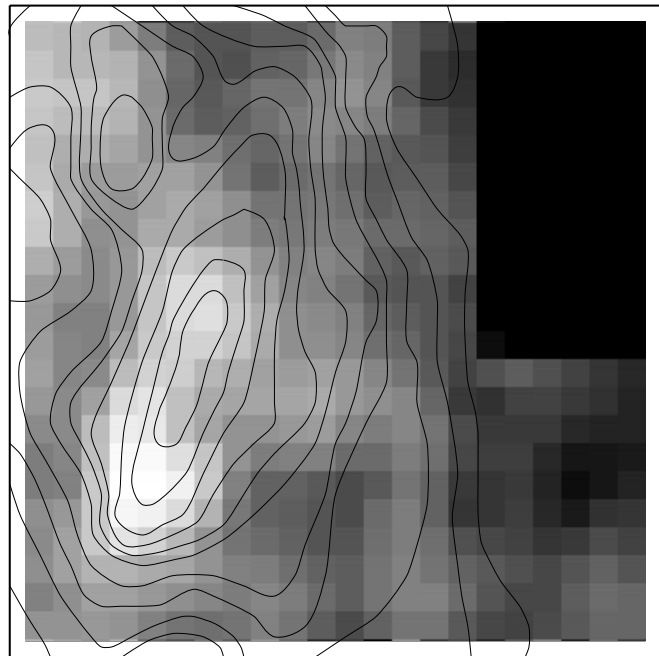
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\* Based on data obtained with the CFHT in Hawaii

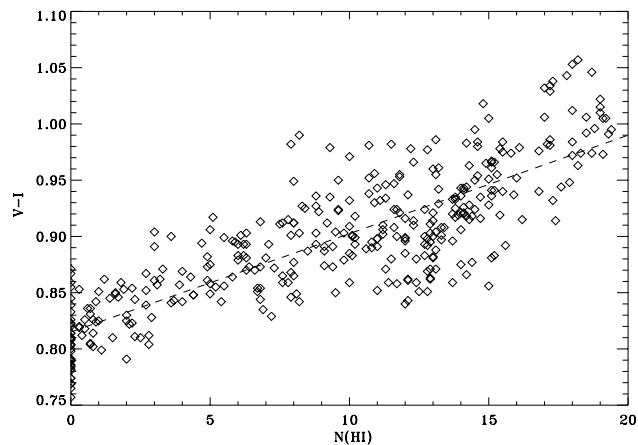
CCD is different because the gain of the amplifier in the reading chain varies slightly from chip to chip. The best procedure would be to sample each chip with the same calibration stars, a very time-consuming operation due to the long read-out time (11 minutes). We preferred to compute the zero-points and colors by using a single setting with a few different SA 113 stars on each CCD. The surface brightness of the sky obtained with each CCD is very similar and shows that the calibration is good. However, after correction with a superflat resulting from the combination of all the available observations made with the mosaic, some discrepancies remain which certainly come from small errors in the color equation. A further correction was thus secured by measuring the  $V-I$  colors of galaxies on the edges of each CCD and adding a constant to each CCD in the  $V-I$  map such that the frontier colors are at the same level. The final internal error for each CCD on the calibration stars is 0.05 mag. in  $V$  and 0.04 mag. in  $I$ , while the external errors between CCDs are respectively 0.02 and 0.04 magnitudes. The measured sky background is  $21.4 \text{ mag. arcsec}^{-2}$  in  $V$  and  $19.3 \text{ mag. arcsec}^{-2}$  in  $I$ , in good agreement with the average observed brightnesses for photometric nights in Mauna Kea.

The algorithm SExtractor (Bertin & Arnouts 1996) was used to separate stellar images from the images of galaxies. The algorithm 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 25.5 was then constructed. This map is shown on fig. 1. It correlates well with the map of the column density  $N(\text{H I})$  of  $\text{H I}$  of Newton & Emerson (1977) corrected for the primary beam response. Figure 2 shows the correlation between  $\langle V-I \rangle$  and  $N(\text{H I})$ . It is clear that we have detected the extinction by dust in the outer disk of M 31. This method was first applied by Zaritsky (1994) then by Lequeux et al. (1995) to search for dust in the halos of galaxies. It is the first time that it gives a convincing result.

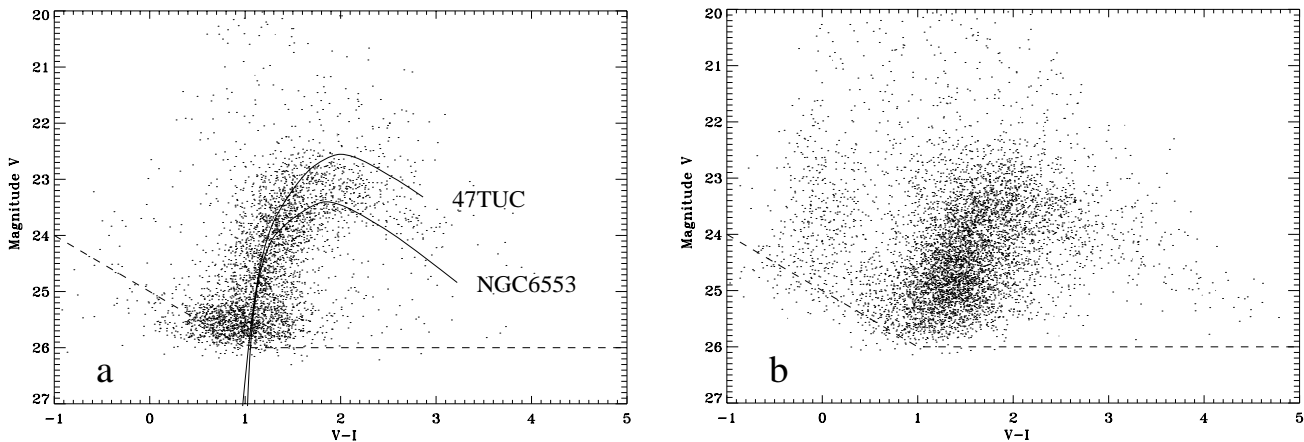
Assuming that the extinction law in the visible is similar for this region of M 31 and for the Solar neighborhood (a reasonable assumption in the visible and the near-infrared according to Bouchet et al. 1985), one has:  $E(V-I_{\text{Cousins}}) = 1.25 E(B-V)$  (Bessell 1976). The regression line of fig. 2 implies that for the observed region  $N(\text{H I})/E(B-V) = 1.1 \cdot 10^{22} \text{ at. cm}^{-2} \text{ mag.}^{-1}$ , about two times the canonical Galactic value of  $5.8 \cdot 10^{21} \text{ at. cm}^{-2} \text{ mag.}^{-1}$ . This is a provisional result which has to be refined by a more detailed study taking into account selection and incompleteness effects. 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 0.5 solar. An alternative to high dust/gas ratio and metallicity is that the studied region contains not only atomic, but also molecular hydrogen with a distribution similar to that of  $\text{H I}$ , the dust corresponding to both components. This is however arbitrary and it would



**Fig. 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  $\alpha(1950)=00^{\text{h}}33^{\text{m}}21.4^{\text{s}}$ ,  $\delta(1950)=+39^{\circ}32'21''$ . The color data are smoothed to roughly the same resolution as the  $\text{H I}$  data ( $3' \text{ EW} \times 5' \text{ NS}$ ), resulting in the loss of the outer part of the image. The size of the outer square is  $28' \times 28'$  ( $5.6 \times 5.6 \text{ kpc}^2$ ). 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  $V-I = 0.74$  (dark) to  $1.06$  (white), on a linear scale. The  $\text{H I}$  contours correspond to column densities of  $(2, 4, 6, 8, 10, 12, 13, 14, 16, 18, 19) \times 7.7 \cdot 10^{19} \text{ atom cm}^{-2}$ . Note the correlation between the reddening of background galaxies and the column density of atomic hydrogen.



**Fig. 2.** The relation between the mean  $V-I$  color of background galaxies and the column density of  $\text{H I}$  corresponding to the image of fig. 1. The regression line corresponds to a dust to gas ratio about half of that in the Solar neighbourhood.



**Fig. 3.** a)  $V$  vs  $V-I$  color-magnitude diagrams for stars in a region of the outskirts of M 31 without detected atomic hydrogen. b) same as a) in regions with a large column density of atomic hydrogen. Figure 3.a shows a giant branch, the beginning of an AGB and an horizontal branch at  $V = 25.5$  mag. ( $M_V = 1.0$  mag.). The location of the giant branches of the Galactic globular clusters NGC 6553 ( $[Fe/H] \approx -0.2$ ) and 47 Tuc ( $[Fe/H] \approx -0.7$ ) is indicated. Contamination by galactic stars and background galaxies is small, and the vast majority of the stars belong to M 31, probably to its halo. Figure 3.b shows the same features but with conspicuous differences, probably due to a disk population and to the effects of extinction and image crowding. There is also a vertical sequence of young, blue stars around  $V-I = 0.0$ , which is absent in fig. 3a.

be surprising that the distributions of  $H I$  and  $H_2$  are so similar. The maximum reddening in the map corresponds to  $A_V = 0.4$  mag.

### 3. Deep color-magnitude diagrams for M 31 stars

During the reduction of the M 31 frames, stars were separated from galaxies. We could then obtain deep color-magnitude (CM) diagrams of these stars. Figure 3a shows the CM diagram for a reference region with low gas column densities and located clearly outside the disk seen in the very deep picture of Walterbos & Kennicutt (1988): it corresponds to the SW of the image of fig. 1 ( $r \sim 26$  kpc). The diagram exhibits a red giant branch, a clear 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. This diagram is similar to  $V$ ,  $V-I$  diagrams obtained with the Hubble Space Telescope for halo fields of M 31 (Rich 1996), but is better defined thanks to the large number of stars. A comparison with the CM diagram of Galactic globular clusters immediately shows that the metallicity of the halo population we observe is fairly high, about  $1/4$  of solar. The high metallicity of the halo of M 31 has first been noticed by Mould & Kristian (1986) and is well confirmed by the present data.

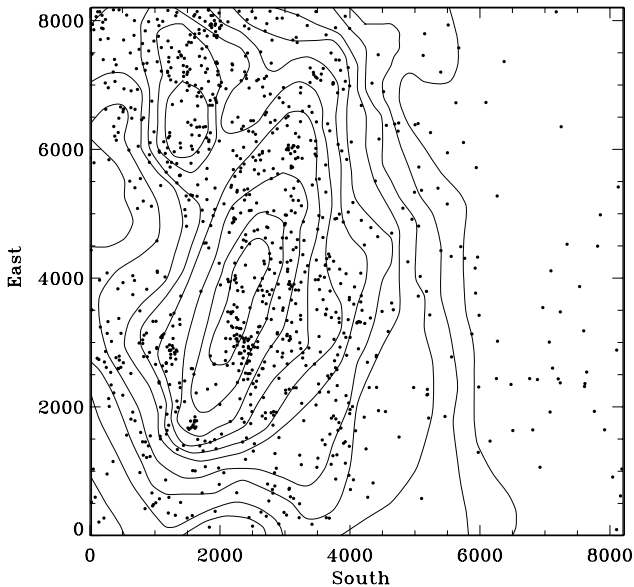
Figure 3b displays a CM diagram for stars in regions with a high gas column density and extinction, in the NE part of the frame ( $r \sim 22$  kpc). The contamination and photometric errors are somewhat larger than for fig. 3a due to a higher density of objects, and variations in the

extinction tend to blur out the diagram, but the giant branch and the AGB are still well visible. The AGB is well developed until  $V-I \approx 4.5$ , indicating a disk population with giants later than M5. This AGB is similar to that in a field 20 kpc from the center (Richer et al. 1990), suggesting a similar, rather high metallicity. The width of the giant branch is large but this may due in part to a spread in the extinction for individual stars. A more detailed study of this effect and of contamination by galaxies, halo stars and Galactic stars (the latter probably weak) is required for a full understanding of this CM diagram.

### 4. Star formation in the outermost disk of M 31

A striking feature of the CM of the outer disk presented on fig. 3a is the presence of blue stars with  $V-I$  around 0.0, as a vertical sequence well separated from the red giant branch. These are main-sequence O-B9 stars. Previously, Hodge et al. (1988) and Davidge (1993) found blue stars in two different fields located at 20 kpc from the center of M 31, but it is surprising to find still active star formation at the very edge of the disk of M 31. Figure 4 is a map of the distribution of blue stars, uncorrected for incompleteness. The correlation with  $H I$  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 relatively devoid of gas.

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



**Fig. 4.** The distribution of the blue stars over the extreme outer disk of M 31. The points represent all the stars brighter than  $V = 24.5$  with  $(V-I) \leq 0.4$ . The contours of the H I column density are superimposed as for fig. 1. The sample of blue stars should be rather complete, but there is some residual contamination by other objects.

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 asymptotic giant branches.

## 5. Discussion and conclusions

We have shown that there are good evidences for a substantial amount of dust in the outermost regions of the disk of M 31, where the surface brightness is as low as  $\mu_B = 26 \text{ mag. arcsec}^{-1}$ . 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 very similar to that of H I, a rather unlikely hypothesis, 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 H I column density and is approximately 0.5 of that near the Sun at 22 kpc radius. This implies in turn surprisingly large values of the metallicity at such large radii. We also find from the aspect of the color-magnitude diagram a metallicity about 1/4 solar in the halo. These high values were not completely unexpected: Jacoby & Ford (1986) have measured an oxygen abundance  $O/H = 3.2 \cdot 10^{-4}$  in an H II region 17 kpc from the center of M 31, and of  $1.2 \cdot 10^{-4}$  in a planetary nebula at 33 kpc projected radius (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 H II region at a kinematic distance of 28 kpc, almost at the edge of the H I 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.

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