CFHT wide–field deep imaging of M 33

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Abstract.

28 $'$ $\times$ 28 $'$ deep V– and I–band images of the center and of the S–E field of M 33 have been obtained at the prime focus of the Canada–France–Hawaii 3.6m telescope. They allowed to map separately the young blue stars, the red supergiants, the red giants and the extreme AGB stars. The disk as traced by red giants has a surprisingly sharp edge. The young blue stars trace the spiral structure very well, but the detailed comparison with HI and CO maps does not show a very good correspondance. The simple spiral–shock model of star formation proposed for the South arm of M 33 is not confirmed. On the edge of the galaxy, star formation starts at a column densit yo fH I o fa b o u t $3 \times 10^{20}$ atom cm$^{-2}$. The colour–magnitude diagram for the halo stars sho ws a broadened red giant branch with a mean metallicit y $[\text{Fe/H}] \approx -1.0$. The shape of the red giant branch confirms the distance modulus of $24.82\pm0.20$ for M 33.

1. Introduction

M 31 and M 33 are the closest spiral galaxies. They are so extended that wide–field CCD mosaics are required to make deep studies of their stellar population over large regions. We have thus decided to observe a field in the outermost disk of M 31 as well as in the disk and in a edge field of M 33 using the 28 $'$ $\times$ 28 $'$ CCD mosaic at the prime focus of the CFH telescope, in the V and I (Cousins) bands. The purposes of these observations are to map extinction in the disks using the statistical reddening of the background galaxies, and to study the stellar populations. Preliminary results for M 31 have been presented by Lequeux & Guédin (1996), but the data are presently being reduced anew. We present here preliminary results for the stellar populations of M 33. The results for the extinction in the disk of this galaxy are not yet available. Section 2 presents the observations and their reductions. Section 3 discusses the distribution of the various stellar population components. Section 4 compares the distribution of young stars with that of the gas. Section 5 discusses briefly the stellar population of the halo of M 33.

2. Observations and reductions

The observations have been made with the UH8k CCD camera at the prime focus of the CFH telescope. The UH8k mosaic is made of eight 2048$\times$4096 pixel thick CCDs arranged to form a square. The scale is 0.206$''$ per pixel and the field is 28 $'$ $\times$ 28 $'$. The
The V, V-I color-magnitude diagram for stars in a field near the center of M33. The dashed line is the estimated 50% completeness limit. Estimated 1-σ errors on V-I are indicated on the right.

CCD at the upper right of the camera suffers from poor charge transfer efficiency and has not been used. The observations were made over two nights in October 1997 under non-photometric conditions with a seeing of 0.9′. 3×5 minutes exposures were obtained in each of the V and I filters with the mosaic centered on the nucleus of M33, and 9×24 minutes exposures in each filter on the SE part of the galaxy. The relative response of the CCDs was obtained by observing large field photometric standards (Landolt 1992) and the zero points of the photometry were calibrated on isolated stars with published V and I photometry (Mould & Kristian 1986). We estimate the internal error (from CCD to CCD) to be 0.02 mag. in each filter and the external error to be 0.05 mag. in each filter.

The photometric extraction of the objects and the separation between stars and galaxies was performed using the recent version 2.0 of SExtractor (Bertin & Arnouts 1996). Details will be given elsewhere (Cuillandre et al. 1999). Approximate completeness limits for stars are V=23, I=22 for the central field and V=25, I=24 for the SE field.

Fig. 1 shows the V, V-I color-magnitude diagram for the stars in a disk field near the center of M33. One distinguishes clearly the blue stars of the main sequence around V-I=0, the bright red supergiants around V-I≈1.5 (with some contamination by Galactic red dwarfs), the numerous brightest red giants with V≤22.5 with the extreme AGB stars at V-I≥2.5. Selecting parts of the V, V-I diagram allow to map the respective populations over the face of the galaxy. Table 1 indicates the selection criteria we have used.
Table 1. Selection criteria for stellar populations.

<table>
<thead>
<tr>
<th>Population</th>
<th>Mag. limits</th>
<th>Color limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue stars (center)</td>
<td>$16 &lt; V &lt; 21.5$</td>
<td>$-1.0 &lt; V-I &lt; 1.0$</td>
</tr>
<tr>
<td>Blue stars (SE)</td>
<td>$16 &lt; V &lt; 23.5$</td>
<td>$-1.0 &lt; V-I &lt; 0.7$</td>
</tr>
<tr>
<td>Red supergiants</td>
<td>$16 &lt; V &lt; 21.5$</td>
<td>$1.0 &lt; V-I &lt; 2.5$</td>
</tr>
<tr>
<td>Red giants (SE)</td>
<td>$22 &lt; V &lt; 24$</td>
<td>$1.0 &lt; V-I &lt; 2.0$</td>
</tr>
<tr>
<td>Extreme AGB</td>
<td>$19.5 &lt; I &lt; 21$</td>
<td>$2.5 &lt; V-I &lt; 4.5$</td>
</tr>
</tbody>
</table>

3. Distributions of the stellar populations

The red giants are distributed smoothly in the disk. The most interesting feature in their distribution is the sharpness of the disk edge as illustrated by fig. 2. The transition between the disk and the halo occurs within about $3.5'$ or $900$ pc at the assumed distance of $925$ kpc (from cepheids; Feast, this symposium), the disk radius being about $11$ kpc. This implies that the stellar orbits must have very low eccentricities at the edge of the disk.

The distribution of the extreme AGB stars (not displayed) is also very smooth showing that they are old enough to have lost the memory of the arms where most of them were probably born.

Conversely, the blue stars are distributed very irregularly. They trace a two-arm spiral structure and many, but not all, are gathered in associations. This is illustrated on fig. 3, 4 and 5.

Finally, the distribution of the red supergiants (not displayed) also shows the spiral structure, although less contrasted. The difference with the blue stars comes in part from contamination with Galactic red stars which are distributed uniformly (Galactic contamination is negligible for the blue stars), and in part from the fact that the red supergiants are older and have had time to partly move away from the spiral arms.

4. Young blue stars and gas

We now compare the distributions of the blue stars as defined in Table 1 with those of atomic and molecular hydrogen. HI maps of M 33 have been published by many authors. The most interesting for our purpose are the interferometric maps of Newton (1980) and Deul & van der Hulst (1987). The latter map results from the Westerbork Synthesis Radio Telescope with the addition of short–baseline information from Effelsberg 100-m observations. Corbelli et al. (1989) have done low–resolution but extremely sensitive HI observations with the Arecibo telescope, which show that atomic hydrogen extends over $2^\circ$, very far from the limits of the two previous observations. A field including the nucleus of M 33 has been mapped in the CO(1–0) line at 2.6 mm with the Amherst radiotelescope (Loinard et al., in preparation), using the same set–up as described by Loinard et al. (1996).

Fig. 3 and 4 show the superimposition of HI line contours and CO line contours respectively, over the map of blue stars for a field in the central region of M 33. One can see that while the gas and the blue stars are all roughly tracing the spiral structure, the detailed correspondence between the three tracers is loose. This can only be due in part to extinction. There are blue stars in regions with little gas, and gas concentrations with or without associated blue stars. The South arm which is conspicuous on the figures is of particular interest in this comparison. This arm has been considered by Courtes & Dubout–Crillon (1971) and by Dubout–Crillon (1977) as the archetype for galactic shock–wave triggered star formation. If this is the case one should find a clear
Red giant stars

Figure 2. The distribution of the red giants in the SE part of M 33. Remark the sharp edge of the disk. The total number of objects displayed on this field is about 40,000. Notice that on the upper central right CCD the completeness limit degrades, hence this area contains less objects. This CCD should not be considered here. Small empty areas are due to foreground bright stars obliterating their direct neighborhood on the CCD image.
segregation between gas and stars of different ages through the arm. Such a segregation is not obvious on fig. 3 and 4, and the red supergiants are also located like the blue stars, in spite of being older in the average. In general, the evidences for galactic shock–triggered star formation are becoming increasingly meager. Conversely, there are increasing evidences in favor of supercloud formation and subsequent star formation by gravitational collapse of gas gathered in density waves or other disk instabilities (Elmegreen 1994).

The comparison between the distributions of HI and of blue stars on the edge of the disk is also of interest. Fig. 5 shows the superimposition of HI contours from Deul & van der Hulst (1987) with blue stars in the SE region of M 33. It is clear that in spite of the presence of HI at larger radii star formation stops when the column density of HI is smaller than $\approx 3 \times 10^{20}$ atom cm$^{-2}$, corresponding to the first contour. A comparison with the maps of Newton (1980) and of Corbelli et al. (1989) gives similar results. Note that the 200 nm UV emission mapped by Buat et al. (1994) also disappears at this column density. In M 31, star formation ceases at an HI column density of $\approx 6-8 \times 10^{20}$ atom cm$^{-2}$ which after deprojection corresponds to the same face-on column density as for M 33. What is the meaning of this threshold? At least two explanations are possible:

- Stars form only when there is molecular hydrogen, and the threshold for star formation corresponds to the threshold for H$_2$ formation. The threshold for abundant formation of H$_2$ is at a column density of about $3 \times 10^{20}$ atom cm$^{-2}$ in the solar neighbourhood (Savage et al. 1977; Reach et al. 1994; Boulanger et al. 1996). However this might just be a coincidence, the threshold for H$_2$ formation being sensitive to the ultraviolet radiation field and to other parameters (see equ. 3 of Reach et al. 1994).
- There is a threshold for instability in the gas and subsequent star formation. Kennicutt (1989) has proposed a simple criterion for gravitational instability but acknowledges that it fails for M 33. Elmegreen (1995) has proposed another criterion for the two–fluid instability in the star + gas system: he defines an instability parameter $Q_{	ext{off}}$ which depends on the surface density and velocity dispersion of both the stars and the gas. Further studies are required to see if this criterion works for both M 31 and M 33.

More generally, our data should allow to reconsider the law of star formation in galactic disks as pioneered by Madore et al. (1974) for M 33.

5. The halo of M 33

Figure 6 presents the V, V–I color–magnitude diagram for stars in the halo of M 33. The giant branch is well defined and the horizontal branch is marginal seen at V$\approx$25.5, near the completeness limit. In order to compare this HR diagram with that of globular clusters, we need to know the reddening. The average between the determinations from the 21-cm line (e.g. Hartmann 1994) and from the foreground stars (Johnson & Joner 1987) is $E(\text{B–V})=0.06$ mag. with an uncertainty of about 0.02 mag. This corresponds to $A_V=0.19$ mag., $A_I=0.11$ mag. and $E(V–I)=0.08$ mag. with the same extinction law as used by Fusi–Pecchi et al. (1996). Comparing our I, V–I color–magnitude diagram with the dereddened diagrams of template globular clusters given by da Costa & Armandroff (1990) we arrive at the following conclusions:

- With the assumed distance modulus $(m-M)_0=24.82$ corresponding to a distance of 925 kpc and the reddening given above, the mean metallicity of the halo is $[\text{Fe/H}]=-1.0$ and there is a metallicity spread from $-0.6$ to $-1.5$. These determinations are not very sensitive to the reddening because of its small value (possible changes by at most $\pm 0.1$ dex).
Figure 3. Comparison between the distribution of young blue stars and of HI in a region of the central disk of M 33. For clarity, the HI map alone is shown on the left panel and the superimposition of the stars and of HI (contours) on the right panel. Coordinates are offsets with respect to the nucleus (diamond) at \( \alpha(J2000)=1\text{h}33\text{m}50.9\text{s}, \delta(J2000)=-30^\circ39'37'' \). The HI contours correspond to column densities of 3 to 21 by steps of 3 in units of \( 10^{20} \text{ atom cm}^{-2} \). The FWHM resolution of the HI map is \( 12'' \times 24'' (\alpha \times \delta) \). The HI map is from Deul & van der Hulst (1987).
Figure 4. Comparison between the distribution of young blue stars and of CO(1-0) in a region of the central disk of M33. Presentation and coordinates as for fig. 3. The CO contours corresponds to integrated line intensities of 0.5 to 4.5 K km s$^{-1}$ by steps of 0.5 K km s$^{-1}$. The FWHM resolution of the CO map is 43$''$. The CO map is from Loinard et al., in preparation.
Figure 5. Comparison between the distribution of young blue stars and of HI in the SE region of M33. Coordinates are offsets with respect to the nucleus. The HI contours correspond to column densities of 3 to 21 by steps of 3 in units of $10^{20}$ atom cm$^{-2}$. The FWHM resolution of the HI map is $12'' \times 24''$ ($\alpha \times \delta$). The map is from Deul & van der Hulst (1987).
Figure 6. The V, V-I color-magnitude diagram for stars in a field in the halo of M33. The dashed line is the estimated 50% completeness limit. Estimated 1-$\sigma$ errors on V-I are indicated on the right.

- However the derived metallicity is sensitive to the adopted distance. One can vary the distance modulus by ±0.2 mag (±80 kpc) without damaging too much the compatibility of the colour-magnitude diagram with the template diagrams. The shape of the red giant branch thus confirms the adopted distance modulus within ±0.2 mag. The mean [Fe/H] would change from -0.8 to -1.2 from the near to the far distance.

Due to the much better statistics and template clusters, our value of the metallicity of the halo of M33 supersedes the value of -2.2 given in the pioneering paper of Mould & Kristian (1986). For M31, we derive from our observations [Fe/H]≈0.6, the same value as given by them.

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References

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