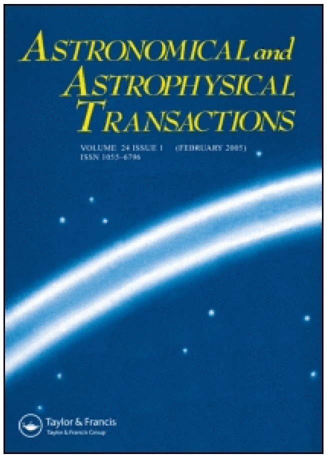

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Yu. N. Efremov [a]; G. R. Ivanov [b]; P. L. Nedialkov [c]
[a] Sternberg Astronomical Institute, Moscow, Russia
[b] Department of Astronomy, University of Sofia, Bulgaria
[c] Astronomical Observatory, Bulgaria

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THE DISTRIBUTION OF BRIGHT STARS AND HII REGIONS IN THE ANDROMEDA NEBULA

YU. N. EFREMOV,[1] G. R. IVANOV[2] and P. L. NEDIALKOV[3]

[1] *Sternberg Astronomical Institute, Moscow, Russia, 119899*
[2] *Department of Astronomy, University of Sofia, Bulgaria*
[3] *Astronomical Observatory, Karcali, Bulgaria*

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The spatial distribution of blue stars in M31 is investigated in relation to spiral arms and HII regions of the galaxy. The global pattern of this distribution is determined by two largest concentrations in the arms N4 and S4. Only in the latter arm (near the complexes OB75, 80, 81) there is a stellar age gradient across the arm and this is connected with an unusually large pitch angle for this fragment of the arm. The most probable value of the radius of corotation in M31 is about 15 kpc and certainly larger than 10 kpc.

KEY WORDS M31, high luminosity stars, HII regions, spiral arms

1. INTRODUCTION

The Andromeda Nebula (M31 = NGC 224) is the nearest spiral galaxy, similar to the Milky Way system in many aspects. Its high luminosity stars are quite bright but, owing to the large angular dimensions of the galaxy, the data on these stars had been limited until recently. There are photographic photometry data for Baade's arms S6 (Baade and Swope, 1963), S4 (Efremov and Ivanov, 1981; Ivanov, 1984) and S5 (Nikolov and Tasheva, 1989) and for a number of star complexes (van den Bergh, 1966; Efremov, 1982). The CCD photometry for a few complexes and other rather small regions has been published recently (Massey *et al.*, 1986; Hodge and Lee, 1988; Hodge *et al.*, 1988). These data complemented with the photometry of some dozen of brighter stars scattered over the whole galaxy (Humphreys, Sitko and Sitko, 1987) serve now as photometric standards together with Arp's photometry in the Field IV (Baade and Swope, 1963).

These investigations focused mainly on the color-magnitude diagram for the regions in question. The global distribution of associations and complexes was studied by van den Bergh (1964) and Efremov *et al.* (1987); for the clusters' this was done by Hodge (1979).

Now, with the publication of a catalogue of bright stars in the field of M31 (Berkhuijsen *et al.*, 1988, hereafter-CBS), the distribution of individual high-luminosity stars can be also studied over the whole galaxy. CBS was used by Berkhuijsen and Humphreys (1989) for the study of the distribution and liminosity function of OB stars in the galaxy. The catalogue is based on the Tautenburg Schmidt UBVR plates and includes 11458 stars with the completeness limit about $19^m.2$ in B. It include about 1000 possible OB stars and about 500 possible red supergiants belonging to M31. CBS is supplemented with the catalogue of 113 blue and 43 red stars, mainly in more crowded regions of M31, obtained with the plates of the 2-m Rozhen telescope (Nedialkov *et al.*, 1989).

In the present paper we use the catalogues of Berkhuisen *et al.* (1988) and Nedialkov *et al.* (1989) to compare the distributions of blue stars and HII regions from the catalogue of Pellet *et al.* (1978), mainly in the ability of both kinds of objects to trace spiral arms and their inner structure.

Until now, indications of the age gradient across the arm have been found only for a fragment of Baade's arm S4 (Efremov, 1980, 1985; Efremov and Ivanov, 1982; Ivanov, 1985). The density wave theory predicts such gradient, providing the pitch angle of the arm and the distance from corotation circle are sufficiently large. Both conditions are realized for the S4 arm (Efremov, 1985) and it is necessary to verify the structure of other arms in the whole galaxy.

2. THE RADIAL DISTRIBUTION OF BLUE STARS AND B/R RATIO

The majority of stars in CBS are foreground stars of our Galaxy. The analysis of color–magnitude and color–color diagrams has led Berkhuijsen and Humphreys (1989) to the conclusion that the stars with $B-V<0.4$ and $U-V<0$ should, as a rule, belong to M31. We have altogether 2072 and 853 such stars at our disposal.

Figure 1 shows the distribution of blue stars ($B-V<0.4$) in the plane of the galaxy. We adopt the distance of 690 kpc, the inclination of the galactic plane to the line of sight of $12^\circ.5$ and the position angle of the major axis of $37^\circ.5$. the concentration to Baade's spiral arms is clearly seen as well as the absence of blue stars closer than 3 kpc to the center. This hole is completely reliable: in our search for blue stars and their groups we were unable to find them closer than 3 kpc to the centre (Efremov *et al.*, 1987; Nedialkov *et al.*, 1989), the absence of HI there is also well known.

There are also two strong concentrations of blue stars, one in the spiral arm N4 which contains the associations from OB29 to OB48 (hereafter, the NE region) and the second in the arm S4 containing OB78 to OB82 (the SW region). The distribution of stars with $U-V<0$ shown in Figure 2 displays similar features.

As a measure of the surface density of bright stars, we have used the total V magnitude per sq. kpc denoted as VT. Figures 3 and 4 give the radial distribution of VT for the stars with $U-V<0$, separately for both sides of the galaxy with respect to the minor axis. Three Baade's arms can be seen on the northern side and five, on the southern one, the peak at 7.2 kpc corresponds to the NE concentration at the eastern part of Baade's N4 arm.

In Figure 5, the radial distribution of VT for the same blue stars is compared with that for red stars with $B-V>1.8$ (dashed line). The maximum of red star distribution is closer to the centre than that for the blue stars. The peak at ~3 kpc is connected with the concentration of red stars at 15′ from the center which is probably unreliable (Berkhuijsen and Humphreys, 1989). Unfortunately, the blink survey of Nedialkov *et al.* (1989) does not cover this region. It is quite improbable for these objects to be red supergiants of M31. These concentrations being excluded, most of red stars fall in the regions of the arms S4 and N4.

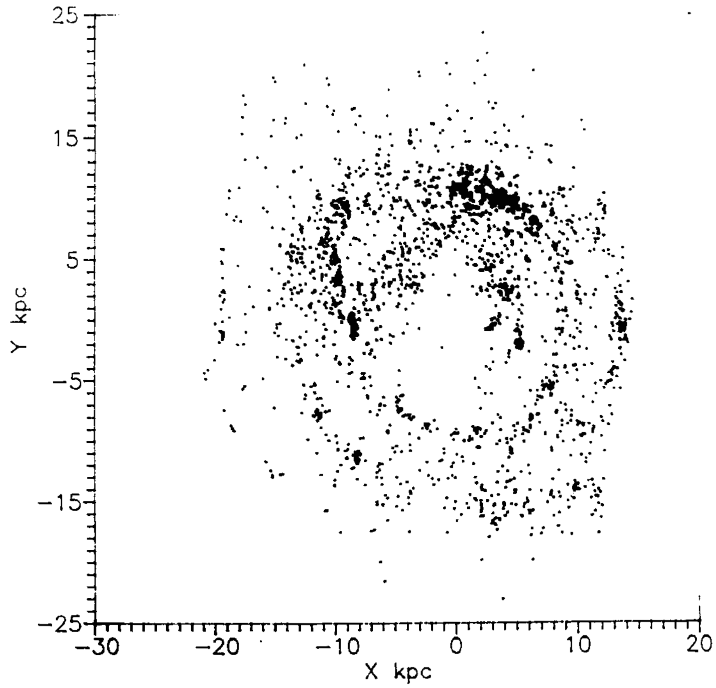

Figure 1 Locations of 2072 blue stars (B−V < 0.4) in the plane of M31.

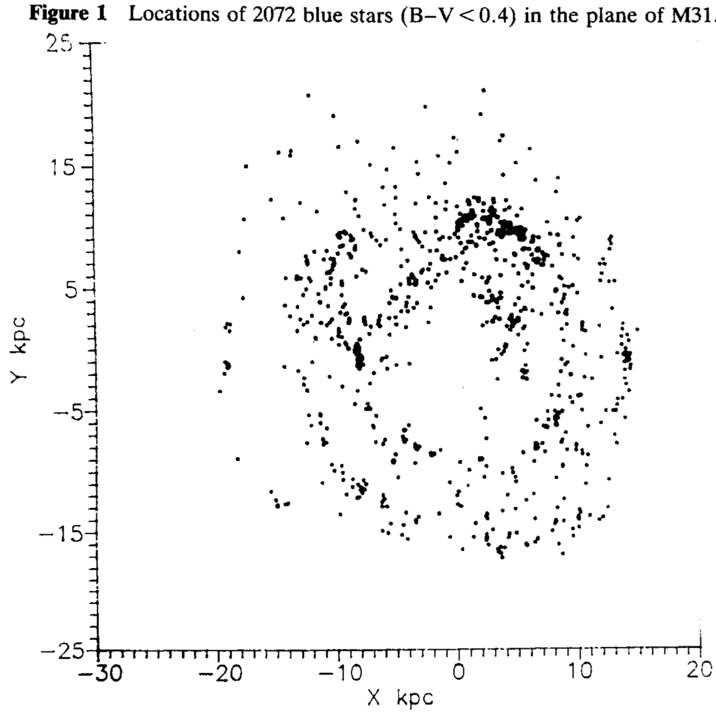

Figure 2 Locations of 853 blue stars (U−V < 0.0) in the plane of M31.

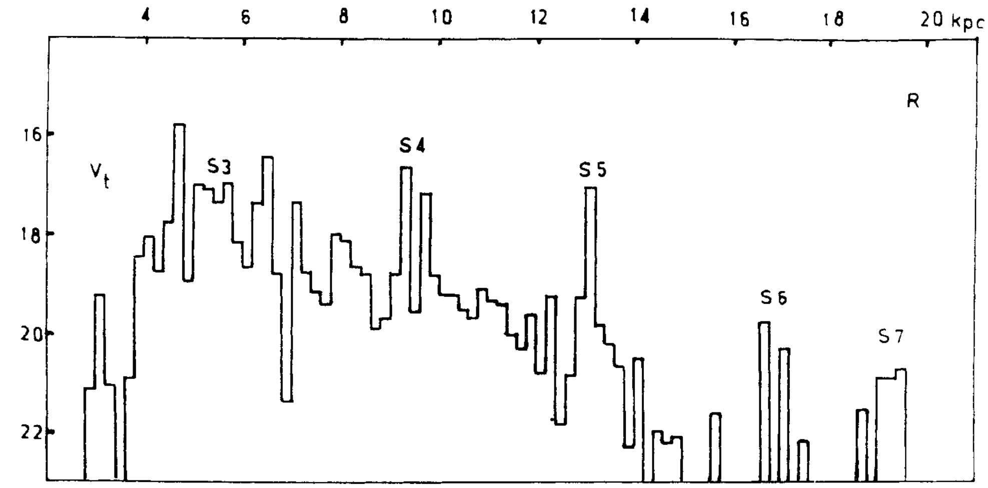

Figure 3 Dependence of the integral brightness VT of blue stars on distance from the center for the southern side of M31.

There is a clear deficit of bright red supergiants in M31 which can be connected with lower rate of massive star formation (Humphreys *et al.*, 1988). We observe 127 such stars in M31 as compared with 1083 such stars (with B–V > 1.8) in M33. To allow for the different completness of the photometry in these two cases, one should consider only the stars brighter $V = 19^m$; then we have 195 red stars in M33 against 127 in M31, the latter galaxy being much larger.

Humphreys (1978, 1980) has shown that the ratio of blue to red stars, B/R, decreases with galactocentric distance both in the Galaxy and M33. the B/R ratio

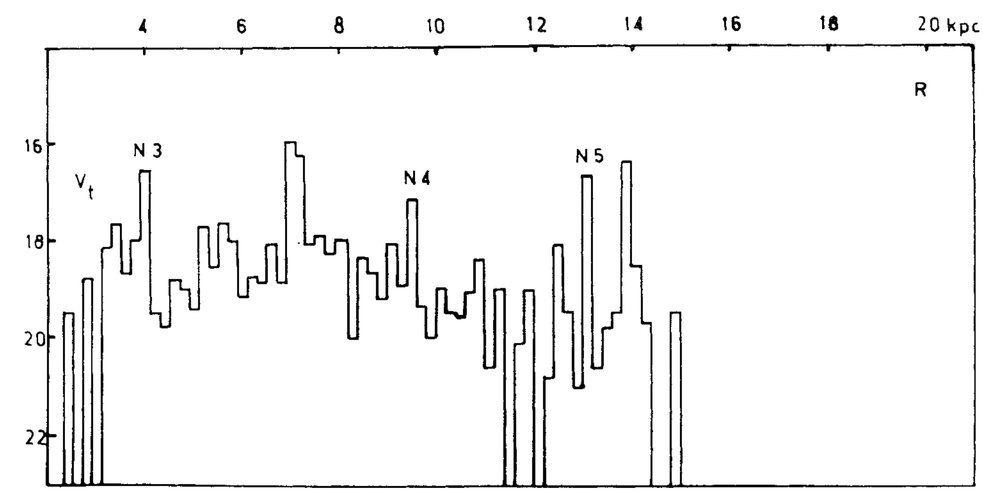

Figure 4 Dependence of the integral brightness VT of blue stars on distance from the center for the northern side of M31.

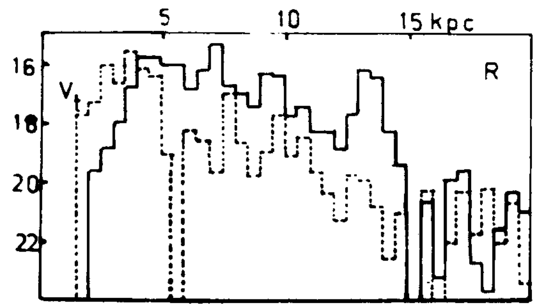

Figure 5 Dependence of the integral brightness VT on distance from the center for blue and red (dashed) stars. The maximum at 2–5 kpc for the latter is unreliable.

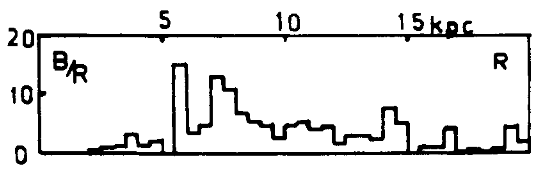

Figure 6 The ratio of the number of blue stars to that of red ones, B/R, versus distance from the center.

is shown in Figure 6 as a function of galactocentric distance; it decreases steeply between 7 to 10 kpc owing mainly to the strong concentration of blue stars in the inner part of the arm N4. The peaks in Figure 6 correspond to the main spiral arms.

3. THE ASYMMETRY IN THE BLUE STAR DISTRIBUTION

Berkhuijsen (1977) pointed out the asymmetry between the northern and southern parts of M31, the HII regions and OB associations being more numerous in the northern part. The radial distribution of VT for 2072 blue stars ($B - V < 0.4$) is given in Figure 7 for the eastern (dashed) and western sides of M31. We see again a high concentration of blue stars in a ring between 4 and 14 kpc and the peaks corresponding to Baade's arms.

The asymmetry between E and W sides in Figure 7 is due to a strong NE concentration of blue stars formed by the stellar complexes OB29–OB48. We found 1332 stars on the eastern side and 740 on the western one whereas Berkhuijsen and Humphreys (1989) found that the E side contains 30% more O stars and blue supergiants predominate there by a factor of 3.

It can be seen from Figure 1 that NE and SW concentrations (which produce the W–E assymetry) have the length of about 8 kpc along the arms. It is highly improbable that this assymetry could be connected with higher internal absorption on the W side of M31 since there are no indications of such possibility (Walterbos and Schwering, 1987; Humphreys *et al.*, 1988). The most likely

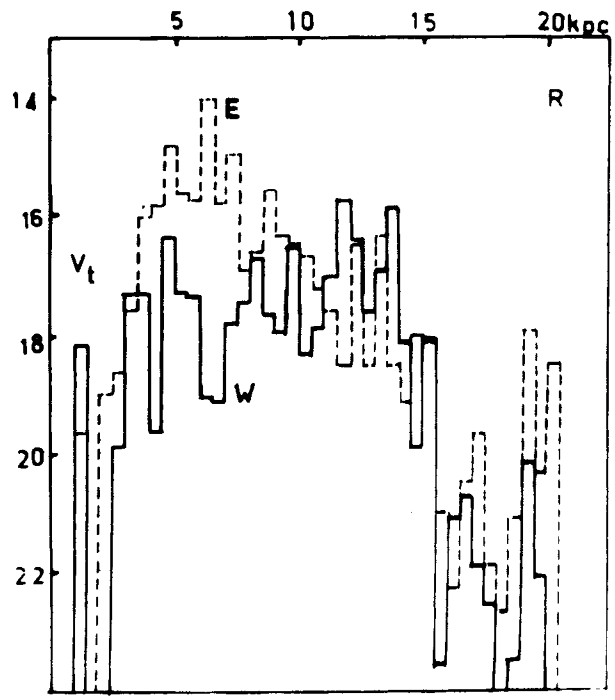

Figure 7 Integral brightness VT versus distance from the center for the western and eastern (dashed) sides of M31.

explanation for both W–E and N–S asymmetry is the highest rate of massive star formation within the fragment of the N4 between OB29 and OB48.

4. THE RELATIVE POSITIONS OF BLUE STARS AND HII REGIONS

We compare now the relative positions of blue stars and brightest HII regions (class 1) from the catalogue of Pellet *et al.* (1978) where their X and Y coordinates are given. The coordinates of blue stars from CBS were transformed into X, Y coordinates with the same position of the galactic centre and position angle of the major axis as used by Pellet *et al.* (1978).

We have found that from 998 blue stars ($B-V<0.4$) only 697 are located within 0.5′ from the centers of 530 brightest HII regions. The surface density of these stars is shown in Figure 8 as a function of distance from the center of the nearest HII region, the unit of density being 0.14 stars per square parsec. This density becomes constant at distances larger than 60 pc (0.3′) and this figure probably reflects the size of aggregates (Efremov, 1989), groupings of O-associations and HII regions.

The distribution of U–B colors of stars over distance from the nearest HII region is shown in Figure 9 for 867 stars with $B-V<0.4$ having both U and B photometry. The overall distribution is bimodal: only the bluest stars (U–B about

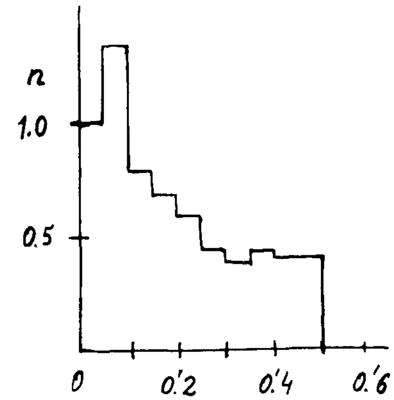

Figure 8 Surface density of blue stars versus distance from the nearest HII region. The density is measured in units of 0.14 stars per square pc.

−1.0) are within 0.5′ from HII regions (422 stars) whereas the stars lying farther away are most numerous at U–B = 0.0. There is a sharp cut-off in their distribution at U–B = −1.2. There is a sharp cut-off in their distribution at U–B = −1.2. All the bluest stars are within HII regions and their colours are probably contaminated by the HII region light. It is also probable that some bluest stars of CBS are actually star-like HII regions because a normal star cannot have such blue color.

The great majority of stars with U–B < −0.4 are within 0.3′ from HII regions and it is possible that most of these stars could be the source of ionization for nearby HII regions. Then these stars should be B0 or earlier types and their

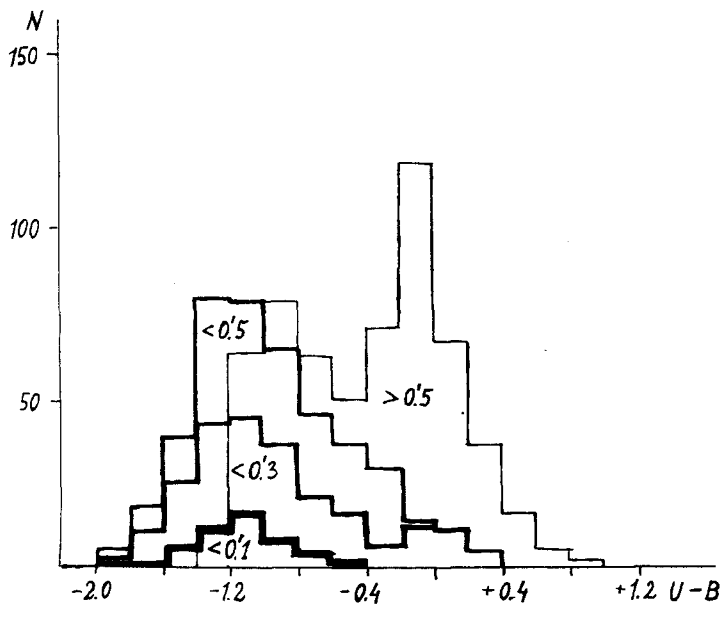

Figure 9 Distributions of the U–B colors of stars over distance from the nearest HII region.

color excess is about 0.4^m–0.8^m, rather large but still possible value for associations in the spiral arms of M31.

It remains to explain the bimodal U–B distributions for the stars lying beyond o′.5 from HII regions (we recall that only the stars with $B-V < 0.4$ are considered here). Probably there are blue stars also within the HII regions of lower surface brightness (the classes 2 and 3 of Pellet *et al.*, 1978) not considered here. The majority of stars with $U-B > -0.4$ (and $B-V < 0.4$) should be B and A supergiants and their indifference to HII regions is not surprising.

5. SPIRAL ARMS DELINEATED BY BLUE STARS AND HII REGIONS

The composite plot of blue stars and HII regions (Figures 10 and 11) clearly shows the concentration of both kinds of objects to about the same spiral features. Many of van den Bergh's (1964) associations—stellar complexes of Efremov *et al.* (1987)—are outlined also by both kinds of objects, though there are important exclusions. For example, the concentration of HII regions in OB59 is not accompanied by blue stars whereas OB122 is noticeable as a concentration of blue stars but not HII regions. This difference is most probably related to the age of the complexes.

Another conclusions based on Figs 10, 11 and 12 concerns the relative displacement of stars and HII regions across the arm. We confirm the conclusion of Efremov (1985) that, in the S4 arm (from OB75 to OB84), nearly all the brightest HII regions are located along the inner edge of the stellar arm (Figures 12 and 13). Now we can see that there are no other fragments of an arm where

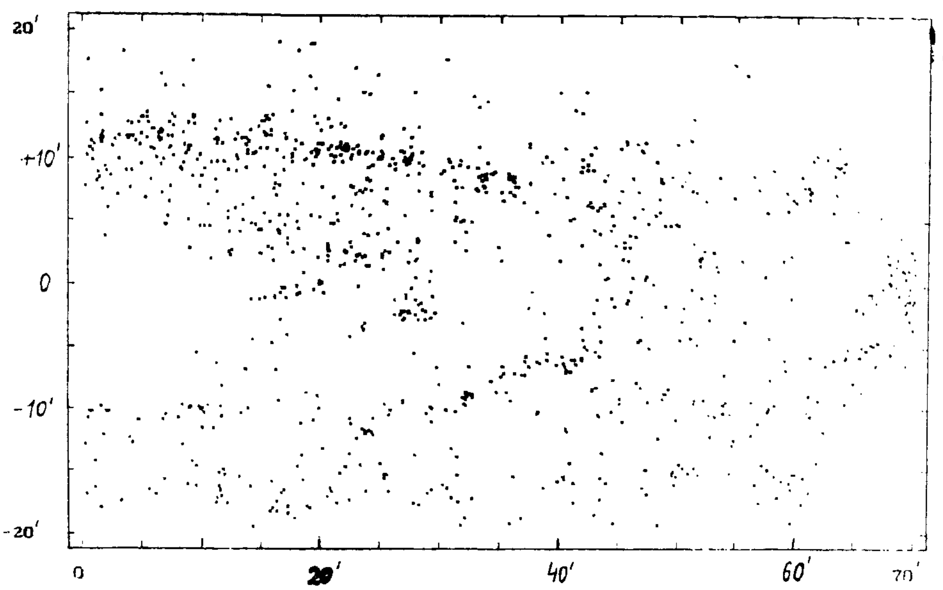

Figure 10 Localizations in the plane of the sky for the northern side of M31 of: 3) stars, $B-V < 0.4$; b) ibidem + HII regions; c) stars, $U-V < 0.0$.

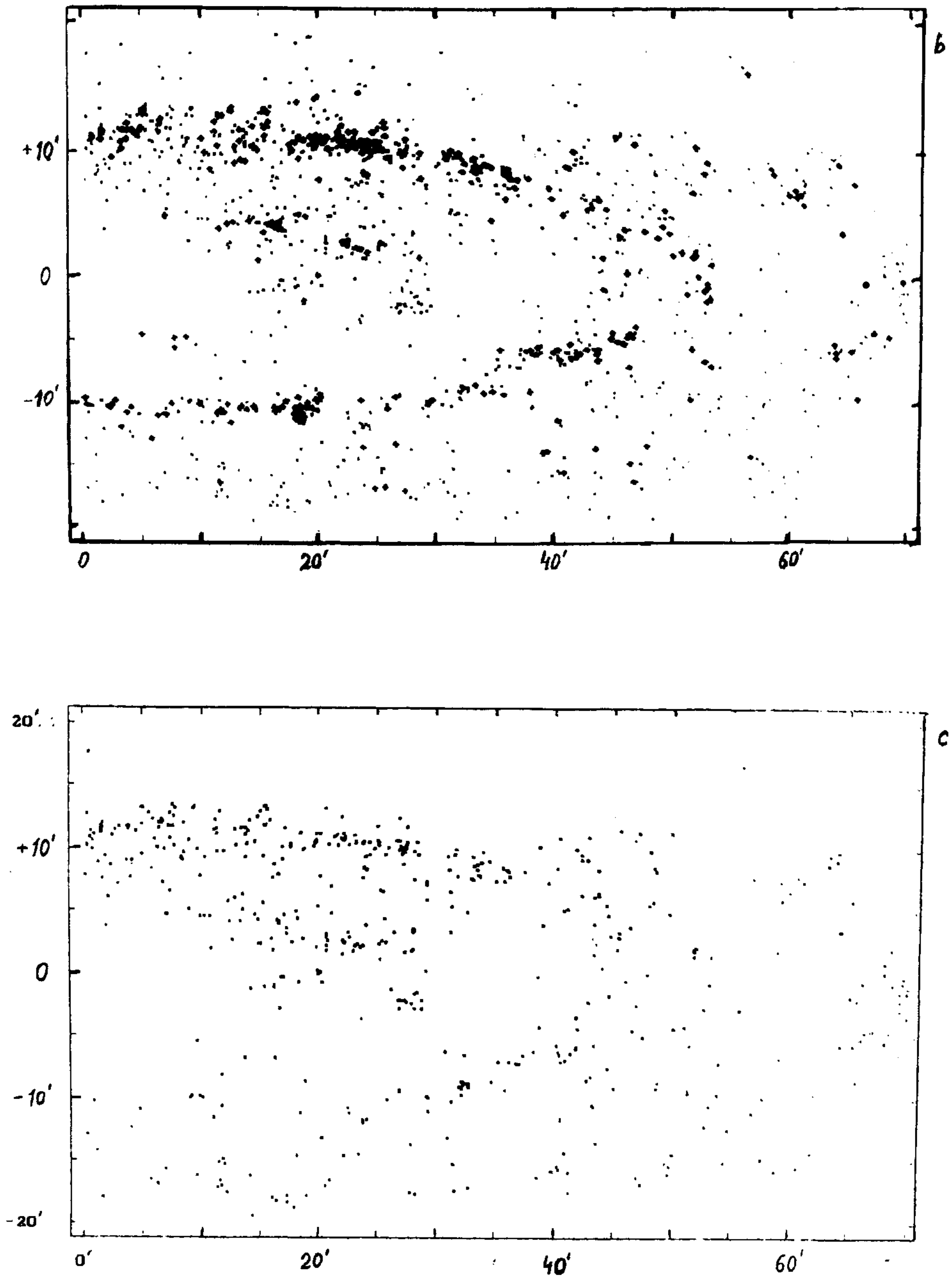

Figure 10—(*Continued*)

the same behaviour of HII regions is observed. Even when HII regions delineate a narrow long filament of an arm, blue stars are well mixed with them or nearly absent, as within the chain of HII regions stretching at $Y = -10$ from $X = -20$ to $X = +30$.

It is especially important to note the absence of a shift between HII regions and blue stars in the fragment of the arm N4 between OB32 and OB48 where the concentration of both kinds of objects is observed to be even higher than in the S4 between OB78 and OB84. Therefore the rate of massive star formation is not directly connected with the occurence of such shift which is one of the manifestations of age gradient across the arm. The various signs of this gradient are known to be present across the S4 arm (Efremov, 1980, 1985; Efremov and Ivanov, 1982; Ivanov, 1985).

It is most probable that the pitch angle of an arm fragment determines the appearance of the gradient, other things being equal. We have argued that the pitch angle is extremely large for the fragment of the S4 arm and this is the reason why the gradient is observed there (Efremov, 1985, 1989); now Figures 1 and 2 confirm this conclusion. This angle is about 30° for the fragment of S4 in question, whereas there is nothing special for N4.

The age gradient in the S4 arm implies the position of corotation at the distance 15–20 kpc from the centre (Efremov, 1989). The conclusion of Sandqvist, Elfhag and Lindblad (1989) that the corotation is closer than 9 kpc to the centre is based on the observation that the maximum of HI is shifted inside the arm relatively to CO at the distance of 9 kpc. These authors have interpreted the shift as a result of dissociation of H_2 moleculs down stream due to the O stars born in molecular clouds at the front of the spiral density wave. But now it appears that only in very

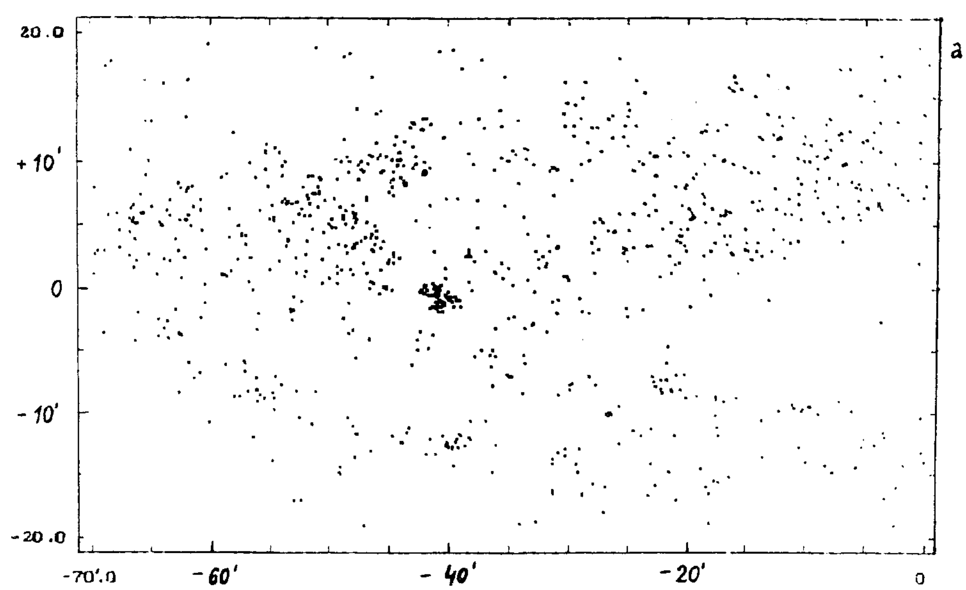

Figure 11 Localization in the plane of the sky for the Southern side of M31 of: a) stars, B–V, 0.4; b) ibidem + HII regions; c) stars, U–V < 0.0.

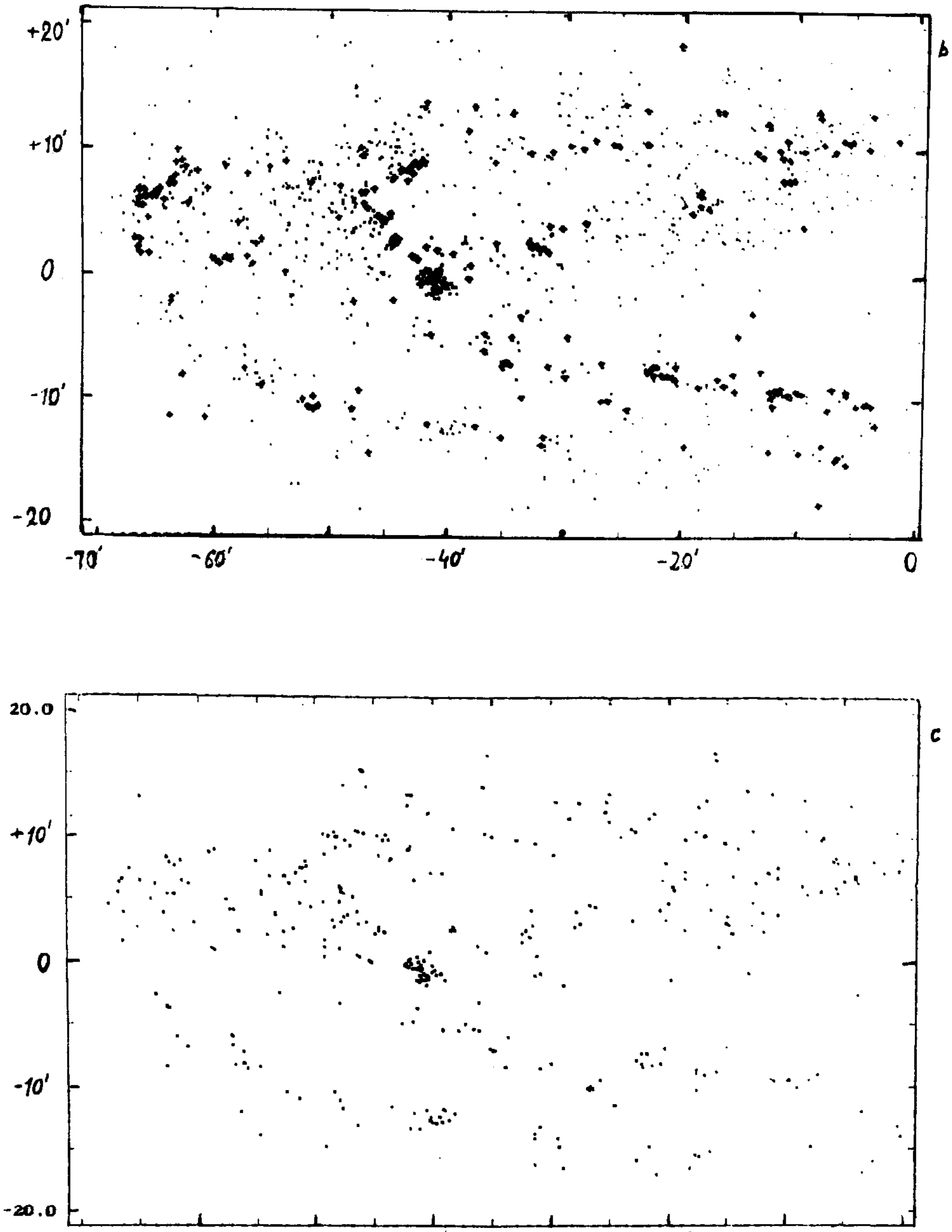

Figure 11—(*Continued*)

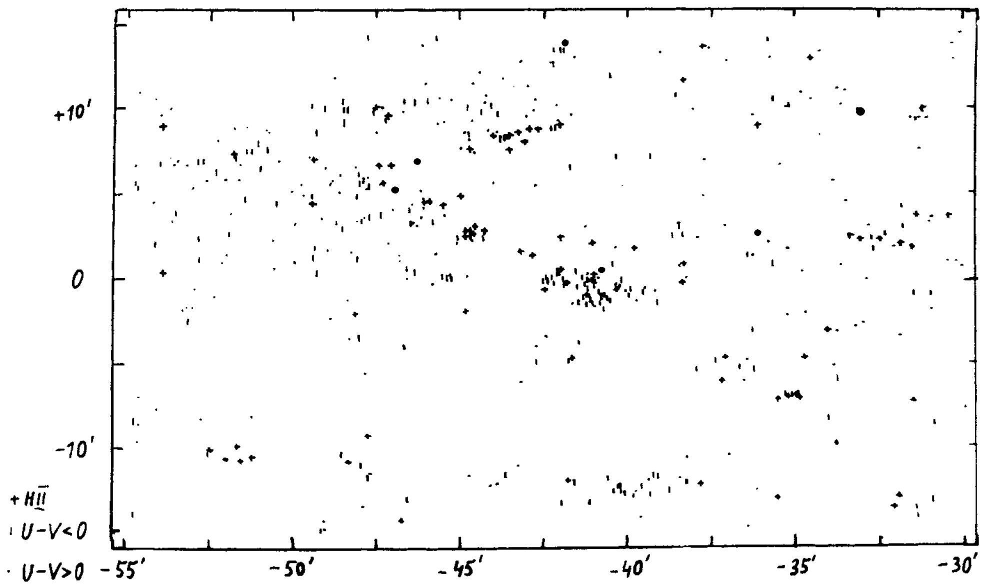

Figure 12 Localization in the southern side of M31 of HII regions (+), stars with U–V < 0.0 (I) and stars with U–V > 0.0 (∗).

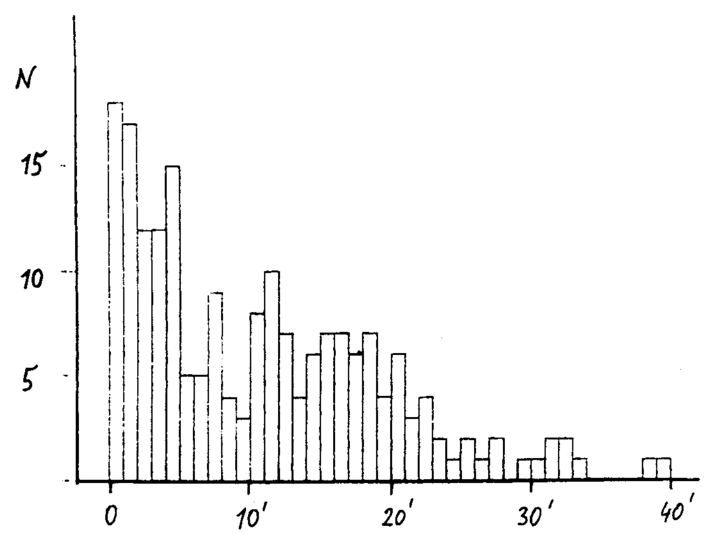

Figure 13 Number of blue stars versus distance from the inner edge of the spiral arm S4 (in the plane of M31) near OB75, 79, 80 and 81.

strong spiral waves, such as those in M51, this time-space sequence of events occurs (Lord and Kenney, 1991). This is not the case for M83 (in contradiction with earlier data) and most probable for M31 also.

The data of Nakano *et al.* (1987) for the S4 arm and Lada *et al.* (1988) for the S3 arm give strong arguments for the suggestion that in M31 (as well as in our own Galaxy) molecular clouds are formed inside HI superclouds when a treshold density is achieved (Kolesnik, 1991). Thus the temporal sequence might be reverse and the observation of Sandquist *et al.* (1989) does not contradict to the location of the corotation beyond 9 kpc. The down stream displacement of H_2 relative to HI may reflect the time needed for the conversion of atomic hydrogen into molecular one. We note also that the age gradient across the S4 arm gives some arguments against the overshooting models of star evolution leading to older ages for the Cepheids (Efremov, 1989). A more detailed discussion of the localization of the corotation in M31 is given elsewhere (Efremov, 1993).

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