

Cepheids as tracers of star formation in M 31^{*}

II. NGC 206: evidence for spiral arm interactions

E.A. Magnier^{1,2,3,4,5}, S. Prins^{1,2}, T. Augusteijn^{1,2,6}, J. van Paradijs^{1,2,7}, and W.H.G. Lewin⁵

¹ Astronomical Institute “Anton Pannekoek”, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

² Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

³ University of Illinois, Astronomy Dept. Bldg. 103, 1002 W. Green St., Urbana, IL 61801, USA

⁴ Astronomy Dept. 351580, University of Washington, Seattle, WA 98195, USA

⁵ Massachusetts Institute of Technology, Room 37-624, Cambridge, MA 02139, USA

⁶ European Southern Observatory, Casilla 19001, Santiago 19, Chile

⁷ Physics Department, University of Alabama in Huntsville, Huntsville, AL 35899, USA

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Abstract. NGC 206 in the Andromeda Galaxy (M 31) is the largest and perhaps the most massive region in the Local Group with coherent star formation taking place on a timescale of ~ 30 Myr. We have incorporated observations of the HI emission and blue stars with our new identifications of Cepheid variables and those from observations by Baade and collaborators to study the star formation history in this region in comparison with the rest of M 31. We find that NGC 206 represents the latest phase of an enhanced level of star formation in the southern region of M 31. NGC 206 is located at the intersection of two spiral arms, suggesting that the interaction between the spiral arms is responsible for the enhanced levels of star formation. The locations of the Cepheid variables demonstrate the motion of the interaction point. We find a relative velocity of 32 km sec^{-1} between the velocity of the stars in M 31 and the velocity of the spiral arm pattern.

Key words: stars: variables: Cepheids – stars: formation – galaxies: individual: M 31 – galaxies: stellar content – cosmology: distant scale

1. Introduction

Spiral and irregular galaxies contain young stars which are grouped together in structures with a large range of scales, from several kiloparsecs to a few parsecs or less. The sizes, distributions, and age ranges of these structures are some of the basic

Send offprint requests to: E.A. Magnier (gene@astro.uva.nl)

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observational constraints on models which describe the processes governing star formation. A variety of mechanisms and scenarios have been described to explain this “texture” seen in galaxies, including such concepts as stochastic collapse of giant molecular clouds, sequential star formation due to the action of the winds and supernovae of earlier generations of stars, and star formation triggered by the passage of the spiral density waves in spiral arms. It is likely that all of these mechanisms are involved in creating the observed texture, but the relative contributions are not well known.

In this paper, we present several pieces of evidence to demonstrate that the giant star formation region in M 31 known as NGC 206 is the result of interactions between the spiral arms of that galaxy. This conclusion is based on observations of the spiral arm structure seen in HI maps (Unwin 1980; Brinks & Shane 1984) in comparison with the distribution of blue stars from the MIT/Amsterdam survey of M 31 (Magnier et al. 1992; Haiman et al. 1993) and the locations of Cepheid variables from observations of Baade & Swope (1962, 1964), and Gaposkin (1963), as well as our new observations (Magnier et al. 1996b – Paper I). In Sect. 2, we discuss the characteristics of young star groups in spiral galaxies and the variety of models employed to describe their formation. In Sect. 3, we discuss NGC 206 as an unusually large star formation region. In Sect. 4, we discuss the observational datasets used in this project, as well as the relationship between the period and age for Cepheids. In Sect. 5, we discuss the evidence for the spiral arm interaction and the implications for the formation of NGC 206.

2. Galaxy texture

It has long been recognized that young stars in galaxies are grouped together into structures with a large range of sizes. On the small scale, there are the open clusters, which have typical

diameters in the range $\sim 1 - 20$ pc, and are loosely bound groups. On the largest scales, the arms of spiral galaxies contain most of the sites of star formation and thus most of the young stars in structures several kiloparsecs long. In between these scales are the OB associations and stellar complexes. Historically there has been some debate over these terms and how they should be applied. Part of the varying usage has been semantic: in similar studies of M 31, van den Bergh (1964) and Efremov et al. (1987) identified more or less the same groupings as “associations” and “complexes”, respectively. There is now a more or less general agreement that the term “association” should refer to the smaller (~ 100 pc-sized) groupings, while the term “complex” should refer to the large-scale (~ 500 pc) groups. There is some evidence that associations and complexes represent fundamental scales for stellar groupings, i.e., star groups are more likely to be found with these sizes, and not intermediate sizes (Efremov 1995).

In addition to the range of spatial scales for the groups of young stars, the range of temporal coherency is also an important observational parameter. In general, the smaller the physical size of the grouping, the shorter the timescale over which the group formed. This trend means that the difference between complexes and associations is both spatial and temporal – the typical association is relatively young, ~ 30 Myr, while the typical complex is somewhat older, ~ 100 Myr. There is an important issue remaining here: should the terms “association” and “complex” be used to describe structures of a particular length scale, or structures of a particular age? The terminology breaks down for those groups that apparently violate the general trend – which name should be used for a very large (~ 500 pc) group which experienced coherent star formation on a short timescale (~ 30 Myr)? Chernin et al. (1995) have recently suggested the term “superassociation”, originally introduced by Baade (1963), for such objects and discussed NGC 206 as an example of such a superassociation.

Models of star formation in galaxies must be able to predict the observed distributions, sizes and age ranges of stellar groupings – what we call the galactic “texture”, in contrast to the large-scale structure (i.e., shape and characteristics of the spiral arms). The mechanisms generally invoked to explain the texture fall into three major classes: stochastic, sequential, and triggered models. Stochastic models discuss the formation in terms of instability mechanisms in gas clouds: thermal instabilities, magnetic instability, and gravitational instabilities (see B. Elmegreen 1993 for a general review). In sequential models, the effects of stellar winds and supernovae create high density regions from which stars form (see e.g., Franco 1992; Shore 1993). Triggered star formation models discuss the formation of stars in terms of large scale density variations caused by galaxy-galaxy interactions and spiral arm density waves (e.g., Combes 1993). Triggered star formation implies that the star formation efficiency, as measured by the ratio of formed stellar mass to H I mass, is higher in the regions of high gas density (ie, spiral arms) while stochastic models imply that the efficiency is constant or determined by local gas parameters, but that the large variations in numbers of young stars produced in the arms

vs the interarm regions, for example, is the result of different gas densities in the two regions. D. Elmegreen (1993) presents evidence that the star formation efficiency does not vary greatly between galaxies with different arm strengths, implying that triggering is not a strong effect, at least when averaged over galaxies. In contrast, Larson & Tinsley (1978) showed that interacting galaxies from the Arp atlas have bluer colors than field galaxies, implying a role for triggered star formation.

In general, all of these mechanisms probably have some role to play, but it is difficult to be sure of the importance of each mechanism. The dissipation mechanisms described by the stochastic formation scenarios certainly play a role in the creation of a star or small group of stars from a gas cloud. The presence of a sequence of ages among certain young stellar groups in the LMC and Milky Way has been discussed as an indication of sequential star formation (e.g., Lortet & Testor 1988). This argument is particularly strong for those regions where the surrounding environment has clearly been influenced by the action of the older generation of stars, as in the case of N44 in the LMC (Parker et al. 1993, Oey & Massey 1995, Magnier et al. 1996a). In this paper, we will show evidence that the extreme star formation region (the “superassociation”) NGC 206 in the Andromeda Galaxy is very likely the result of arm-arm interactions.

3. NGC 206 as a superassociation

NGC 206 is an extreme example of a region of recent star formation. Although its $H\alpha$ luminosity is lower than those of the giant H II regions in M33 (NGC 604 & NGC 595) or 30 Doradus in the LMC, it is larger and more massive than any of these other associations: the diameter of NGC 206 is ~ 850 pc, compared to 200 pc for 30 Dor, 225 pc for NGC 604, and 150 pc for NGC 595. In Fig. 1, we compare the IMFs of these four associations, as measured by Parker & Garmany (1993) for 30 Dor, using ground-based observations, Drissen et al. (1993) for NGC 604 and NGC 595 using HST observations, and Odewahn (1987) for NGC 206 using ground-based observations. These comparisons show that NGC 206 has ~ 2 times the mass of 30 Dor and ~ 4.5 times that of NGC 604, assuming parallel IMFs. Furthermore, the IMF for NGC 206 is based on ground-based observations with substantially lower resolution, so that some of the stars may in fact be double or multiple stars. This confusion implies that the total mass of NGC 206 may be even larger than cited here.

Notice that we do not consider NGC 206 to be a complex, although it is similar in size to these structures. NGC 206 represents a region for which the star formation has taken place within the past 20-40 Myr, as is evident in the large number of stars with masses $> 10M_{\odot}$ (Odewahn 1987). This is a much shorter timescale than the > 100 Myr over which complexes are thought to form. It is reasonable to assume that the relatively small amount of $H\alpha$ emission of NGC 206 compared to that of NGC 604, NGC 595, and 30 Dor is due to a difference in the ages of these systems. The age difference may result in a reduced $H\alpha$ luminosity through two effects: 1) The most mas-

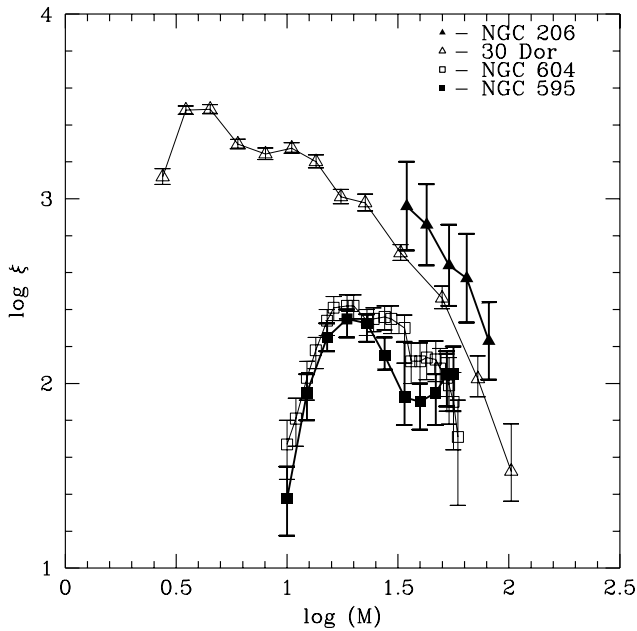


Fig. 1. Comparison between measured initial mass functions for 30 Dor (from Parker & Garmany 1993), NGC 206 (Odewahn 1987), NGC 595 and NGC 604 (Drissen et al., 1993).

sive stars, which emit the highest fraction of Lyman continuum photons responsible for the observed $H\alpha$ emission, have died in NGC 206. 2) The effects of winds and supernovae from the supergiant stars in the system may have cleared the region of the ambient hydrogen needed to create the $H\alpha$ emission. This suggestion is supported by the presence of an H I hole at the location of NGC 206 (Brinks & Bajaja 1986). The unusual size and mass of NGC 206 suggest that its formation may have been the result of an unusual circumstance.

4. Observational data

In order to study NGC 206 in relationship to its local environment, we have used three sets of data on M 31 relevant to the star formation. We have used the H I survey of Unwin (1980) to trace the locations of the spiral arms. Although the Brinks & Shane (1984) H I survey of M 31 has a higher resolution, we have not used it because our goal is to trace the large-scale features of the arms. The resolution of the Unwin (1980) survey is well matched to this purpose. The features discussed below are also apparent in the observations of Brinks & Shane (1984).

We have used the blue stars in M 31 to trace the youngest stellar population. The deepest and most complete photometric survey of M 31 is the MIT/Amsterdam *BVRI* CCD survey (Magnier et al., 1992; Haiman et al., 1993). This survey covered ~ 1.7 degrees² of the main optical disk of M 31, and is complete to $V \sim 21.5$. Finally, we have used Cepheid variables to trace a somewhat older stellar population.

4.1. Cepheids as age indicators

Classical Cepheids can be used to trace populations of different ages, because the pulsation period of a Cepheid is related to its age. The Cepheid variability occurs when the star passes through the instability strip, after the star has evolved away from the main sequence. The mass of the star determines the period of the variability, and the mass is also directly related to the main-sequence lifetime of the star. Therefore, the age of the star can be determined from the period of the oscillation. This relationship was first discussed in the 1960s (Young 1961; Efremov & Kopylov 1967), and has since been confirmed observationally (see Tsvetkov 1988 for an overview).

The calibration of the period-age relationship as described by Tsvetkov (1988) has not been updated to account for recent advances in the stellar evolution tracks and opacities. We have attempted to improve the calibration by employing the recent tracks of Schaller et al. (1992), converted to colors and absolute magnitudes using the spectral catalogs of Kurucz (1991). We have located the points where the Schaller et al. (1992) tracks cross the blue and red edges of the instability strip in the color-magnitude diagram, using the solar metallicity tracks. For each point, we have found the absolute V magnitude and the corresponding age of the star. We fitted a line to the M_V , $\log A$ (age) points, and used the M_V , $\log P$ (period-luminosity relationship) of Freedman & Madore (1990) to find a relationship between $\log A$ and $\log P$:

$$\log A = 8.4 - 0.6 \log P$$

where A is the Cepheid age in years and P is the period in days.

There are several possible sources of error in this determination. First, the choice of the boundaries of the instability strip has some effect, though this is small because the stars cross this general portion of the color-magnitude diagram fairly horizontally and on a short timescale. Therefore, errors in the choice of the instability strip do not strongly affect the absolute magnitude or age of the star. The difference between the absolute magnitude for a given track at the blue and red edges of our instability strip was less than 0.2 mag, and the difference in the ages was typically smaller than 10^4 years. A more significant uncertainty is caused by the fact that the stars more massive than $\sim 5M_\odot$ cross the instability strip in three places, instead of only one. The time span between these multiple crossings is not very large (typically $\sim 10^4$ years) because the entire evolution is so quick, but they do occur at significantly different absolute magnitudes. These extra loops cause a Cepheid of a given age to have a range of absolute magnitudes of ~ 1.0 mag. This is the dominant source of error in the relationship and results in an uncertainty of the age of a Cepheid of ± 0.15 in $\log A$. There is also some error introduced by the scatter in the period-luminosity relationship, the error in the observational determination of M_V , and the somewhat higher-than-solar metallicity of M 31, but these errors are much smaller than the error due to the multiple crossings.

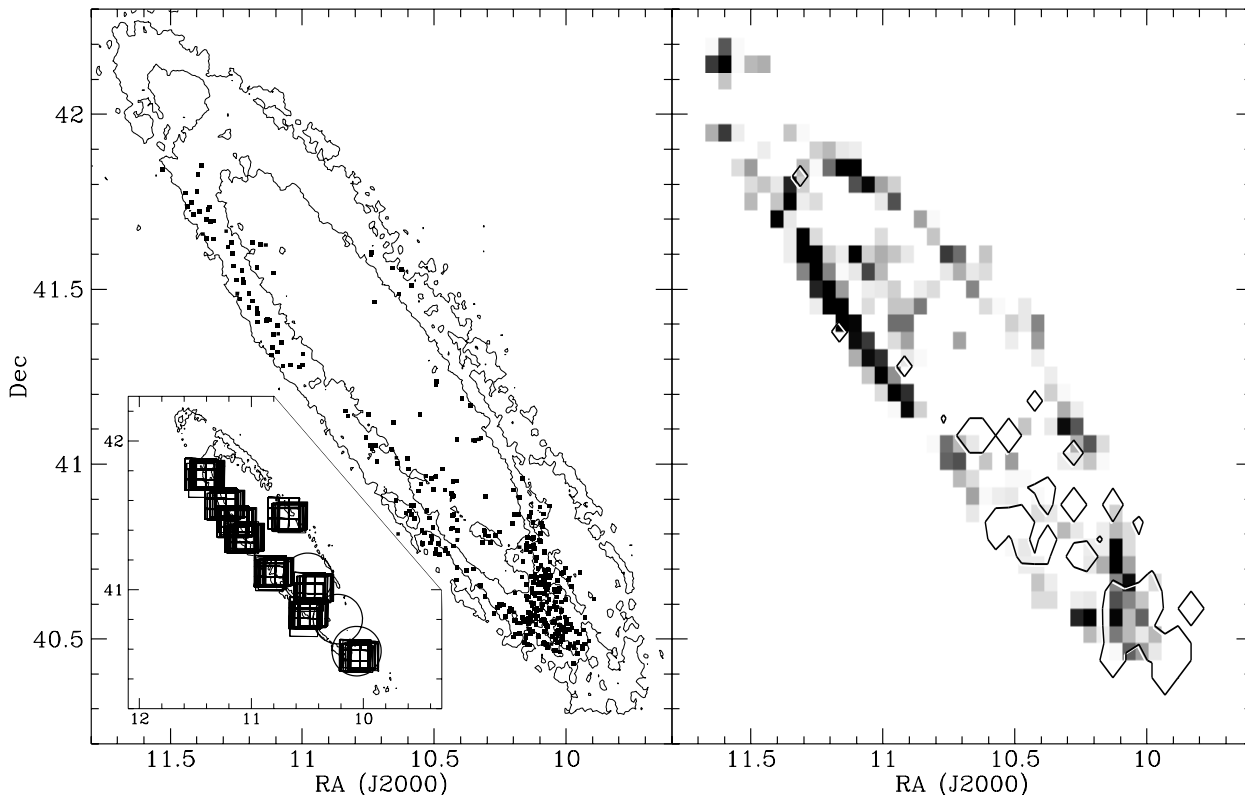


Fig. 2. Left: Distribution of all observed Cepheids in M 31, overlaid on an HI contour map (Unwin 1980). The inset shows the regions which have been observed (squares: Paper I; circles: Baade & Swope 1963, 1965; Gaposhkin 1962:). Right: the greyscale shows the density of blue stars ($B - V < 0.2$), the contours show the regions with Cepheids / blue stars > 0.5 . There is a clear excess of Cepheids in the region south of NGC 206, which is located at 10.1, 40.75.

4.2. Observations of Cepheids in M 31

Substantial work has already been done to identify Cepheids in M 31 using the observations of Walter Baade (Baade & Swope 1962; 1964; Gaposhkin 1963) and Hubble (1929), primarily to improve the determination of the distance to M 31, and thereby improve the determination of the extragalactic distance scale. These searches were limited to a small portion of M 31 (see Fig. 2) and ignored the spiral arm regions, where star formation is most active.

We have recently performed a variability study of 9 fields along the eastern spiral arm regions and parts of Baade’s Fields I, II, and III (see Fig. 2). We have used this data set to identify Cepheids. The observations were performed using both the 2.5m Isaac Newton Telescope (INT) at the Observatorio de Roque de los Muchachos, La Palma, and the 1.3m McGraw-Hill telescope of the Michigan-Dartmouth-MIT (MDM) Observatory at Kitt Peak. Each of the 9 fields in our program was observed ~ 35 times. The observations at the INT were performed between Sept 9 and Sept 17, while those at MDM were performed between Sept 24 and Oct 4, 1993, giving a total baseline of 24 days. The details of the analysis of these observations and the resulting identifications of the individual Cepheid variables have been reported elsewhere (Paper I).

In the case of the above samples of Cepheids in M 31, the combined selection effects of the limited number of the most massive stars and the magnitude limits of the searches combine to constrain the typical detected Cepheid periods to a range of ~ 2 days – ~ 50 days which, as described in Sect. 4.1, corresponds to a range in ages of ~ 24 – 165 Myr, with the bulk of the Cepheids having predicted ages in the range 50 – 100 Myr. The average age of the Cepheids in this sample is ~ 70 Myrs, and the peak of the distribution is at 89 Myr. The sample of Cepheids used in this study traces a substantially older population than the bright, blue stars.

5. NGC 206 as the result of an interaction

Figs. 3 and 4 show the distribution of the three star-formation tracers described in Sect. 4 for the southwest portions of M 31, in the region of NGC 206. Fig 3a shows just the distribution of the gas seen in HI. In this figure, several arm structures can be seen. Baade (1963) defined a series of arms in M 31 based on the positions of HII regions and dust lanes. The arms he described, however, represent in general the large rings of star formation and do not correspond well to many of the detailed structures seen in HI maps. The bulk of the structures visible in Fig 3a correspond primarily to his arm S4. We will now describe in

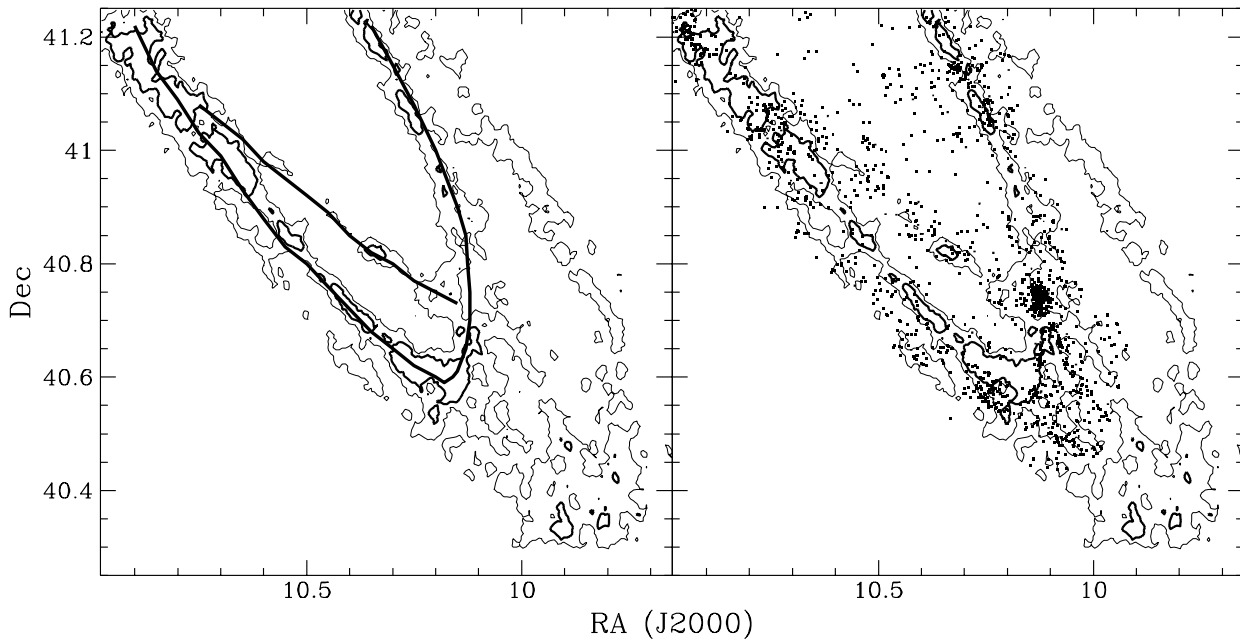


Fig. 3. Left: H I contour map (Unwin 1980) of the region around NGC 206. The two spiral arm segments are marked. Right: H I contour map including blue stars (Magnier et al., 1992; Haiman et al., 1993). NGC 206 is the large group of blue stars at 10.1, 40.75.

some detail the structures seen in this region. On the western side, starting at $\alpha, \delta = 10.3, 41.2$ and progressing towards the southwest are two distinct arm structures. On the eastern side, starting at $\alpha, \delta = 10.9, 41.2$ and progressing again to the southwest is a larger arm structure that apparently separates into at least two isolated arms by $\alpha = 10.6$ (highlighted with a solid line), and possibly a third further south. The region south of $\delta = 40.6$ is highly confused, with several structures pointing in several directions. One reason for the confusion here and the overlap of the arms in the vicinity of $\alpha, \delta = 10.9, 41.2$ is the warp in the disk. Based on the kinematic structure in the H I, Brinks & Burton (1984) showed that the warped disk causes the spiral arms in this region to be projected on the same line of sight. They point out that the nodal line of the warp is along the major axis of the galaxy. In Fig. 3a, we have used solid lines to highlight two arm features which seem to meet.

Fig. 3b shows the same H I map, this time with the locations of the blue stars from the MIT/Amsterdam survey marked with small dots. These stars are chosen to have $B - V < 0.2$ and $V < 21$. This selection makes this a complete sample of stars which are typically quite young, $\lesssim 30$ Myr. The choice of the color cutoff excludes foreground Galactic stars, which have $B - V > 0.4$ and includes the upper end of the main sequence, as well as some of the young, massive supergiants. We have chosen $B - V < 0.2$ even though this is somewhat redder than the main sequence at $V \sim 21$ magnitudes for M 31, to avoid rejecting stars with relatively large errors in their colors. In this figure, NGC 206 can be clearly seen as a very large clump of blue stars, located at the intersection of the two arm features marked in Fig. 3a. The H I hole at the location of NGC 206, noted previously by Brinks & Bajaja (1986), is also clear in this pair of figures.

The coincidence of NGC 206 and the intersection of the two spiral arm segments suggests that NGC 206 has formed as a result of the interaction of these two arms. This interpretation gains support when the Cepheid distribution is considered.

Fig. 2a shows the distribution of known Cepheid variables throughout M 31, overlaid on the H I map. The Cepheids in this figure have been identified in the classic work of Baade and collaborators (Baade & Swope 1962; 1964; Gaposkin 1963) and in our recent observations (paper I). These two sets of data do not cover the entire disk portions of M 31 and it is important to be aware of the regions which have not been observed. A map of the coverage of the two surveys is shown in the inset to Fig. 2. The Cepheids shown in all of these figures have been chosen with $V < 21.0$, at which level the completeness of both surveys is similar. The most striking feature of the Cepheid distribution is the disparity in the ratio of Cepheids to blue stars between the bulk of the galaxy and the regions south of NGC 206. Fig. 2b shows a contour map of this ratio overlaid on a grayscale plot showing the density distribution of blue ($B - V < 0.2$) stars. The contour is set to a threshold where the ratio of Cepheids to blue stars in a spatial bin is greater than 0.5. Throughout most of the star formation regions in M 31, the ratio of Cepheids to blue stars is less than 0.2. In the regions around NGC 206, the ratio rises to 0.5 - 2.0. We note that the blue stars used for this figure have a completeness around 21 magnitudes, and therefore represent the upper portions of the main sequence, with ages which must in general be $\lesssim 30$ Myr.

This large difference in the Cepheid-to-blue star ratio can be understood if there is a region with an enhanced level of star formation in the south which has moved during the past ~ 100 Myr relative to the spiral arm structure seen today. In this

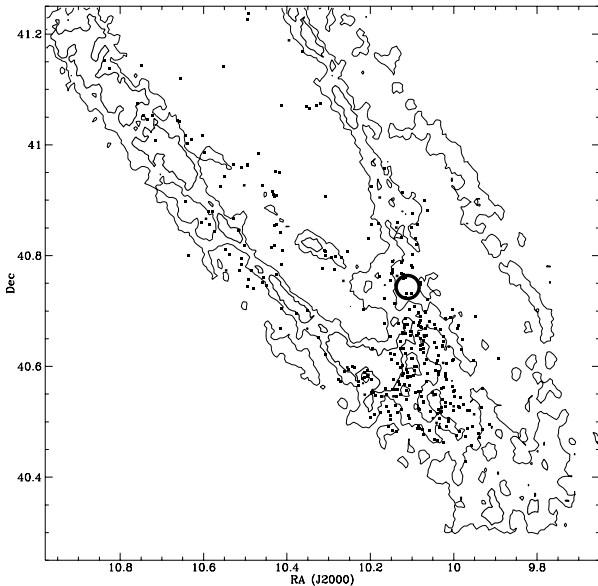


Fig. 4. Cepheid distribution in the region around NGC 206. The location of NGC 206 is marked with a thick circle.

description, NGC 206 represents the most recent phase of this enhanced star formation. The presence of the nodes of the warp of the disk (Brinks & Burton 1984) and the apparent intersection of the two spiral arms seen in Fig. 3 suggests that the cause of the enhanced star formation is due to interactions between the spiral arms in this vicinity. The distribution of the Cepheid variables shows that this level of active star formation has been continuing in this region for at least ~ 150 Myr.

Fig. 4 shows the distribution of all Cepheids with $V_{\max} < 21$ in the southern region of M 31, in the vicinity of NGC 206. The very large number of Cepheids in the regions south of NGC 206, marked with a large circle, can easily be seen in this figure. The displacement of the region with extra Cepheids relative to NGC 206 shows the rate of motion of the region of enhanced star formation, and presumably the motion of the location of the nodal line of the warp relative to the stars in the disk of M 31. We assume a typical age of 90 Myr for the bulk of these Cepheids and 30 Myr for NGC 206, and take the displacement to be the distance between NGC 206 and the rough center of the large group of Cepheids ($\alpha, \delta = 10.1, 40.55$). This distance ($\sim 0.15^\circ$) corresponds to ~ 1900 pc at the distance of M 31, giving a relative velocity of ~ 32 km sec $^{-1}$, with an error of ~ 15 km sec $^{-1}$. This concrete measurement of the motion of the spiral arm structure in the disk is an important piece of input data to model descriptions of the disk dynamics. The sources of error in the determination of this number are the range of typical ages for the Cepheids and NGC 206, and the difficulty of determining the center of the group of Cepheids. There is one point of concern for our description of the interaction. If our hypothesis is correct, that the elevated number of Cepheids is due to an ongoing interaction, then one would expect a general trend of Cepheid age with position in the region with excess Cepheids. However, there does not seem to be such a trend. The Cepheids

throughout this region seem to have ages between 50 and 100 Myr. The explanation may simply be that the measurements of the age (from either period or luminosity) are too inaccurate to show such a trend, or it may be that the interaction takes place over a large scale in the arm, so there is not a coherent trend on small distances and timescales. Further observations of Cepheids in this area, in particular to improve the period determinations and increase the depth of the sample, would help to further test the hypothesis.

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