SPIRAL STRUCTURE IN M31

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ABSTRACT

Luminous spiral arm features in M31 are presented as they would appear if the galaxy were to be viewed flat-on. The logarithmic spiral which best fits the star arms is $r = 30'e^{0.13\theta}$. The arms trail in rotation. Like other spirals studied by Danver, the pitch steepens somewhat to the inside and becomes slightly shallower to the outside. The derived pitch angle for the M31 spiral is $\mu = 83°$, which is tightly wound compared to the average for spiral galaxies of $\mu = 75°$. Even though M31 is tightly wound, it is pointed out that the distance between arms in M31 is about 4 kpc, or more than twice the distance that appears to separate arms in our own Milky Way system.

The spiral pattern outlined by 688 emission nebulae in M31 and the tilt of their plane are difficult to interpret. They occur predominantly between 8 and 14 kpc from the center and in some places they outline arm segments very well. If it is assumed that all emission nebulae are in a single, flat plane, however, then there is no projection factor which will give a rectified picture which looks like a continuous spiral curve.

The most acceptable interpretation seems to be that the major part of M31 has an inclination of $i = 16°$. The disk, however, is raised on the near side out of the plane to an inclination near $i = 11°$, and this deformation persists into the vicinity of M32. M32 appears to be responsible for the deformation of the M31 plane, but since M32 appears projected off the end of a major spiral arm, it is possible that the perturbation may not be purely gravitational but may instead be partially or wholly plasma-magnetic.

I. INTRODUCTION

One of the results which came out of the initial survey of the emission nebulae in M31 was that they appeared to outline the spiral arms exceedingly well. Baade spoke of the H II regions as lying along segments of the arms like "beads on a string." Around this time, Morgan, Osterbrock, and Sharpless (1952) obtained distances to emission nebulae within a few kiloparsecs of the Sun and for the first time succeeded in outlining spiral structure in our own Galaxy.

Consequently, Baade was very excited by the prospect of being able to plot the emission nebulae positions, corrected by a tilt factor, and thus obtain a precise picture of the spiral arms in M31 as they would look if the galaxy were to be viewed flat-on. The results in the present paper show that this expectation was not fulfilled and that the emission nebulae present a picture which is difficult to interpret. I surmise that this is what led Baade to say in 1958 that the complete disentanglement of the spiral structure could not be done by H II regions alone but would require a study of the dust and gas and population I stars as well.

The interpretation of the pattern of the emission nebulae is discussed here. At the same time, I have made an attempt to describe and measure the over-all spiral structure of M31 in terms of what we ordinarily refer to as the spiral structure of a galaxy. The aim is to present a necessarily approximate, but nevertheless quantitative, picture of the spiral structure in M31. It will, I hope, enable progress to be made on the important problem of finding out just what roles ionized and unionized gas, dust, and stars of various kinds play in the role of creating and maintaining in spiral structure a galaxy.

II. CRITERION OF SPIRAL STRUCTURE

Generally an extragalactic nebula is called a spiral if its outer parts are in the form of luminous tubes coiled more or less around the center in a spiral pattern. It does not matter whether a disk of stars is present or absent or whether dust or bright stars can be seen. It is simply the presence of luminous features in a spiral pattern which defines the class of objects. Hubble (1936) classified spirals this way. Danver (1942) measured morphological parameters of many spirals, and it is to the luminous arms that his measures refer.

It would be important for many reasons to have a clear picture of what M31 would look like at a greater distance and viewed perpendicular to the plane. But, because of the nearly edge-on tilt to our line of sight, and probably also due in smaller measure to the presence of a strong disk and irregularities in the arms and perturbations of the plane, it is difficult to get a clear impression of the nature of the spiral pattern. Figure 1 shows an experiment by William Miller, photographer at Mount Wilson and Palomar Observatories, aimed at making the spiral arms more easily visible. Negative and positive plates made from a photograph taken with the 48-inch Schmidt telescope were slightly offset and printed together to obtain the picture in Figure 1. The nebula looks as if it were backlighted. This gives a psychological effect of a third dimension and renders the spiral arms more noticeable. What appear as the most conspicuous luminous features in M31 were then traced off and represented as crosshatched areas in Figure 2. Normal black-and-white photographs gave the same results when the main spiral features were traced. Figures 1 and 2 are shown on the same scale and directly aligned so that the reader may judge the nature of the features which I have adopted as defining the spiral structure and the accuracy of the schematic representation.

III. FLAT VIEW OF M31

The schematic representation of the spiral arms in Figure 2 may be viewed perpendicular to the plane if all the minor axis (Y) coordinates are multiplied by the appropriate factor which will correct for the tilt. This has been done in Figure 3, where a factor of 3.6 was found to give the best representation (corresponding to a tilt angle $i = 16°$). Various logarithmic spirals were tried, and it was found that the best fit to the cross-hatched segments of spiral arms was

$$r = 30' e^{0.13\theta} .$$

The fitting accuracy is about $30' \pm 3'$ and 0.13 ± 0.02.

The projection factor of 3.6 seemed to give the best over-all appearance to the arms in Figure 3. It should be noted, however, that two arms on the north side would look better with larger projection factors (N5, 4.2 or $i = 14°$, and N4, 3.8 or $i = 15°$). From his inspection of the blue stars, the emission nebulae and the dust lanes, Baade (1958, 1963) found the arm crossings along the major axis of M31. They are marked in Figure 3, where it is seen that Baade's arm crossings are correctly connected by the log spiral whose equation is given above. The arms, marked completely independently by the surface-luminosity criterion alone, as in Figure 2, agree very well with the arm crossings marked by Baade. Furthermore, Figure 3 shows that the pitch of the fitted logarithmic spiral would have to steepen up toward the center to join up with Baade's inner arms (crossings 3, 2, and 1), and the pitch would have to flatten toward the outside to agree with arm crossings 6 and 7. This behavior is typical of spiral galaxies as shown by Danver (1942).

In order to get an additional and completely independent determination of how the spiral structure really would appear in M31 if we could view it flat-on, an attempt to rectify the nebula photographically has been made. Figure 4 shows how an exposure of M31 taken with the 48-inch telescope looks when printed on a platen which is inclined 15° to the line of sight. (Photograph courtesy of William Miller.) Circular objects are naturally elongated; there is some defocusing on the top and the bottom of the image and the magnification varies from the top to the bottom. Nevertheless, the photograph closely resembles a fairly normal spiral galaxy as seen in large numbers in more distant

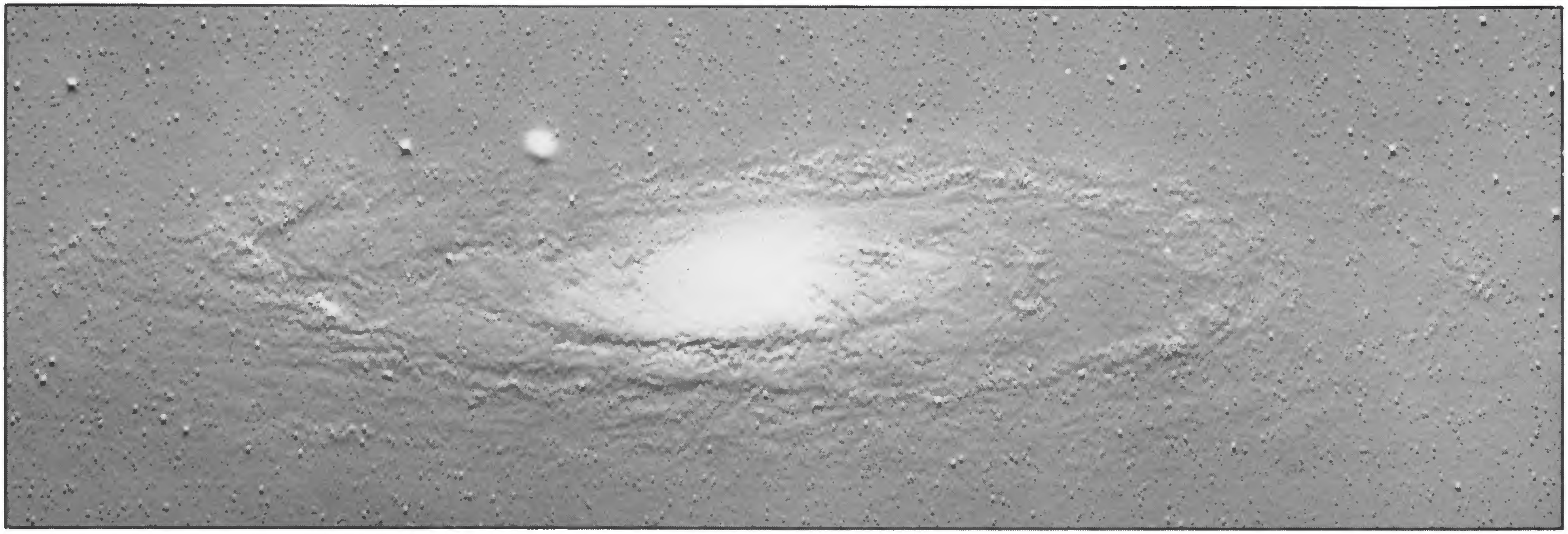

FIG. 1.—Negative and positive prints of M31, slightly offset, and printed together. Purpose is to highlight the spiral features. (Photograph by William C. Miller)

FIG 4.—Photograph of M31 which has been printed on an easel tilted 15° from edge-on Despite the elongation of the circular nucleus, defocusing, and variable magnification from top to bottom, the main spiral features appear approximately as they would if M31 were viewed flat-on Comparison with Fig 3, which is drawn to the same scale, shows that the two major spiral arms, N4 and S4, wind up in the direction of rotation (counterclockwise) (Photograph by William C Miller.)

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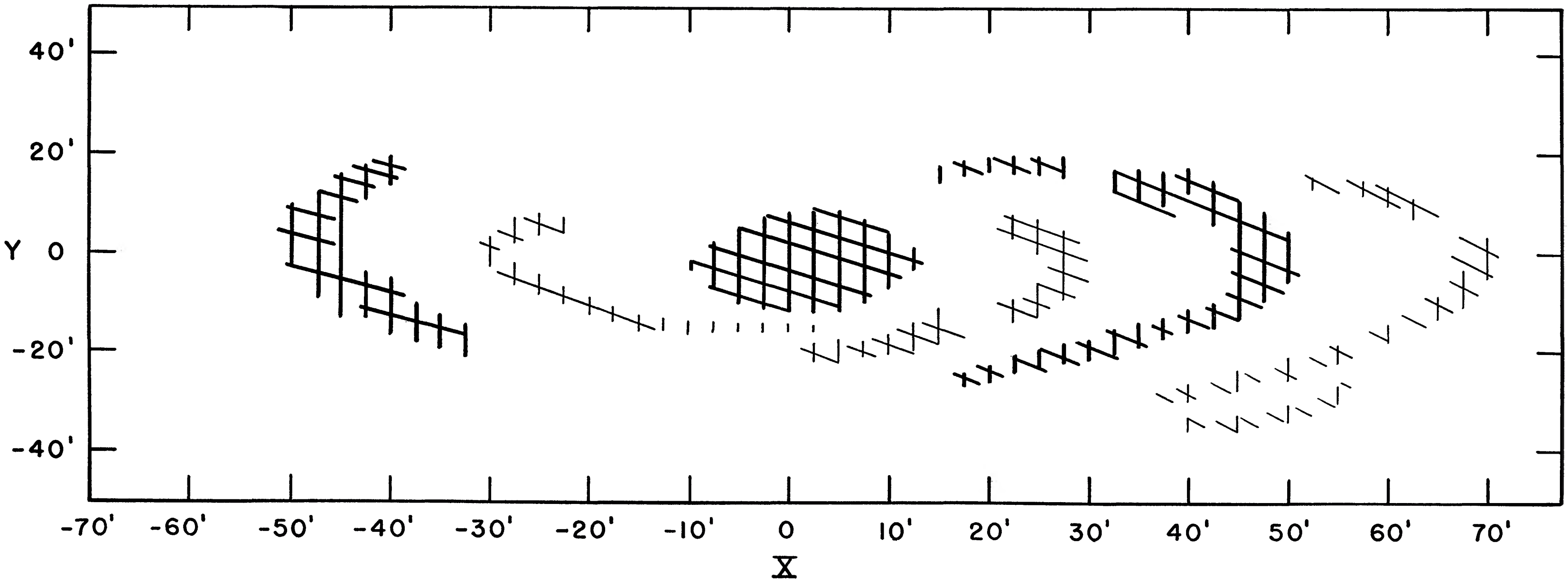

FIG. 2.—The major spiral features as traced from Fig. 1. Heavy shading indicates the strongest features and light shading a less strong class of features. Only the light (luminous) spiral arms have been sketched and the dark features ignored as much as possible.

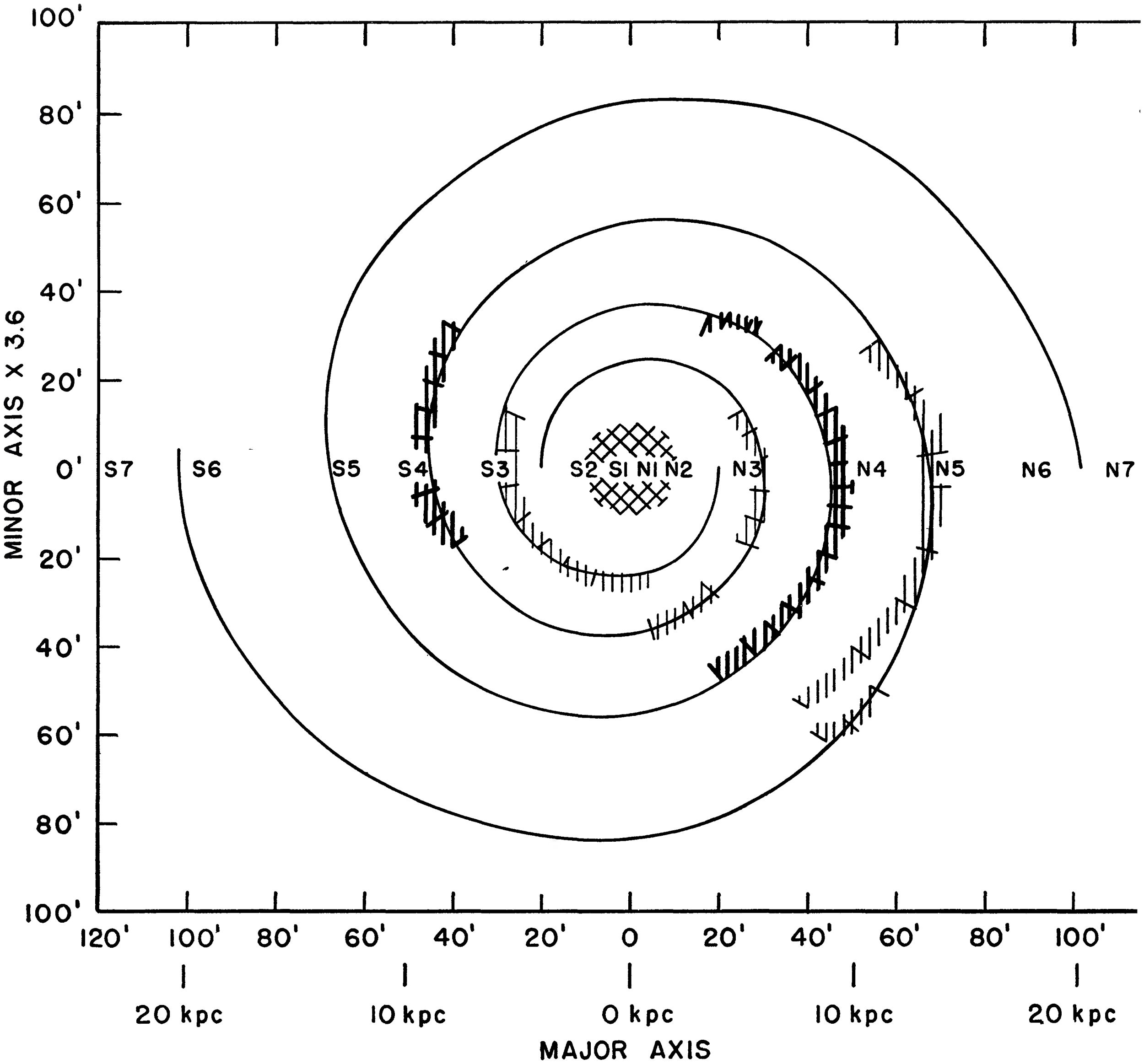

FIG. 3.—The minor axis coordinates of the crosshatched spiral features in Fig 2 have been multiplied by a projec factor of 3.6 The log spiral $r = 30'e^{0\ 13\theta}$ is a good fit as drawn, except for the innermost regions where the pitch shoul steeper and the outermost where the pitch should be flatter. Baade's arm crossings are numbered north and south a the major axis.

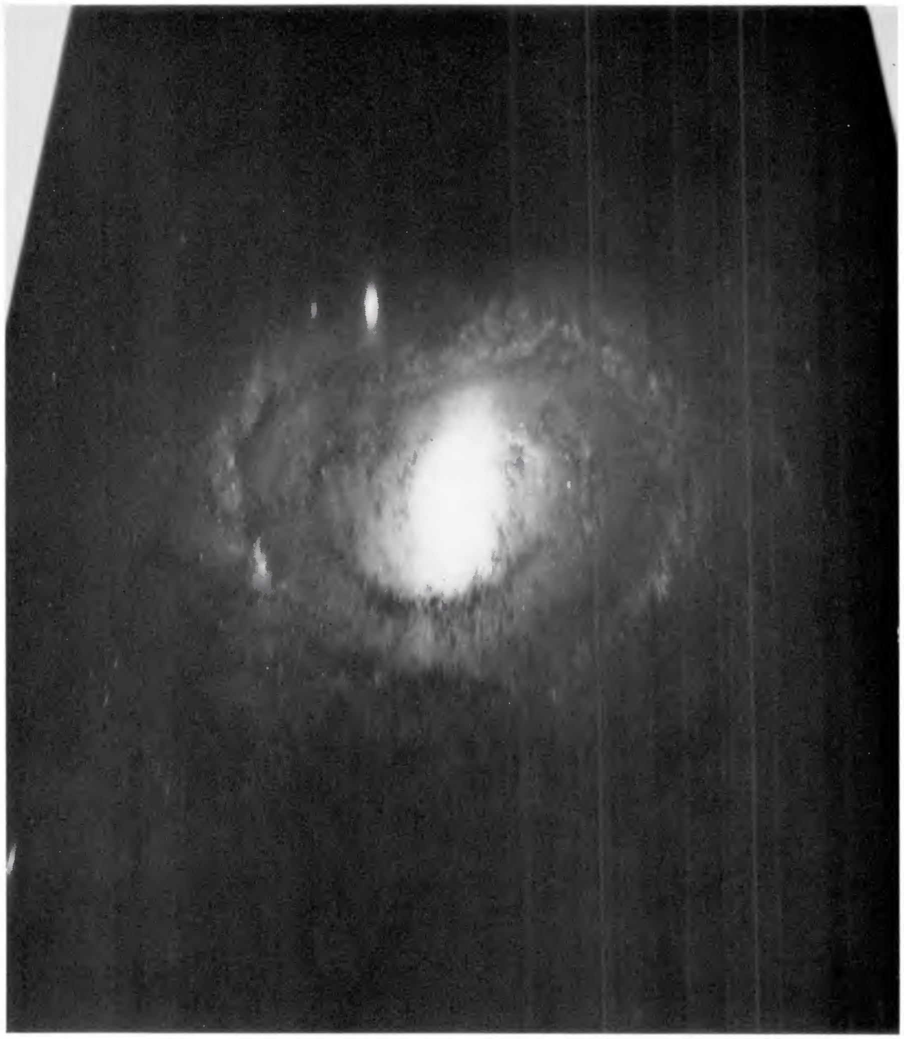

FIG. 4.—Photograph of M31 which has been printed on an easel tilted 15° from edge-on. Despite the elongation of the circular nucleus, defocusing, and variable magnification from top to bottom, the main spiral features appear approximately as they would if M31 were viewed flat-on. Comparison with Fig. 3, which is drawn to the same scale, shows that the two major spiral arms, N4 and S4, wind up in the direction of rotation (counterclockwise). (Photograph by William C. Miller.)

regions of space. In particular, it confirms the schematic result in Figure 3 in that it shows two main spiral arms on either side of the nucleus, N4 and S4, opening out in a direction opposite the rotation (the spiral is rotating in the direction of winding up).

It is of value to note that the platen on which the erected image of M31 was printed was tilted until, by eye, the spiral pattern looked best (most flat-on). Later the tilt angle was recorded. It turned out to be $i = 15°$, which gives an independent check on the angle of $i = 16°$ derived from the schematic spiral arms.

IV. SPIRAL PATTERN OF M31 COMPARED TO OTHER GALAXIES

In the present paper we will take the results of Sections II and III on the luminous star arms as defining the average spiral pattern of M31. In particular, the log spiral shown in Figure 3 can be compared to patterns in other spiral galaxies.

Danver (1942) fitted logarithmic spirals to ninety-eight galaxies. He found that the pitch angles for the spiral varied from $\mu = 54°$ to $\mu = 86°$. The average for Sb spirals was $\mu = 75°$. The pitch angle found here for M31 is $\mu = 83°$. We see, therefore, that M31 is very tightly wound, even for an Sb which is in general slightly tighter wound than an Sc. Another way of stating this is that if there is a correlation of earlier nebular type with flatter pitch, then M31 is indicated to be an early Sb (in the direction of Sa).

Another result obtained in Sections II and III is that a constant pitch angle affords a good average fit over most of the visible arms in M31, but that this pitch steepens toward the center and flattens toward the outside. This same result came out of Danver's analysis of spirals in general.

It is difficult to so place our own Milky Way into this group of galaxies because the pitch of the spiral arms discovered in our own Galaxy is so far quite uncertain (Oort, Kerr, and Westerhout 1958).

One thing is very clear, however—our picture of M31 gives a two-arm spiral with the major arms occurring in the region of $R = 9$ kpc distance from the center. Those arms are separated from adjoining arms by a well-determined 4 kpc on the average. (The distances between the S5-S4-S3 arms are 3.8 and 3.4 kpc, and between the N5-N4-N3 arms are 4.0 and 5.0 kpc.) In our own Galaxy the distance to the next outer arm from us has been found by all investigators to be about 2 kpc and the distance to the next inner arm a little less than that. At 10 kpc we are at about the same distance from the center as the major spiral arms are in M31, but our arms are more than twice as close together as those in M31!

The first important conclusion to be drawn is that if we are really observing separate arms in our own Galaxy, as is currently believed, then either we are a multiple-arm spiral or we are much more tightly wound than M31. If our own Galaxy were a two-arm spiral, this would imply a pitch angle of $\mu = 86°$ and place our own Galaxy on the extreme limit of pitch angles for galaxies in general. Our Galaxy would fit much better into the average run of galaxies if it turned out that the spiral arm in which the Sun is situated was only a local bifurcation and that our arm joins either the next outer or next inner arm a little further along in the direction of rotation. If our Galaxy turns out to be multiple-armed, then it would imply it was more like an Sc than an Sb in this respect (Arp 1962).

If the picture continues to be as it is at present, with individual arms in our own Galaxy separated by only about 2 kpc, then we must exercise extreme care if we compare our Galaxy to M31 or any other two-arm spiral of roughly 20 kpc in diameter.

V. EMISSION NEBULAE

a) Rectifying the Projected Distribution

When the 688 emission nebulae which were catalogued in the proceding paper (Baade and Arp 1964) are multiplied by a tilt factor of 3.6 ($i = 16°$) and plotted, the distribution shown in Figure 5 results. Instead of outlining a spiral pattern, the emission nebulae suggest two concentric oval rings. Now it is possible that M32 lies in the plane of M31. In that case, the emission nebulae could still lie in a flat plane but be elongated by the presence of M32 into some degree of true ellipticity. This would appear to be substantiated by the fact that the apparent major axis of the distribution in Figure 5 lies at a considerable angle from our selected major axis in the sky ($Y = 0$ axis). The south-preceding axis in Figure 5 is tipped by 26° and the north-following by 15°. If we had merely used an insufficient tilt factor, the distribution would be expected to be still elongated along the original axis. If the above case is true, and we cannot prove that it is not, then the true angle of inclination for M31 would be $i = 16°$, and we would have an acceptable interpretation.

When the previously derived logarithmic spiral is drawn through the points in Figure 5, however, Figure 6 is obtained. Figure 6 shows that the majority of segments of emission

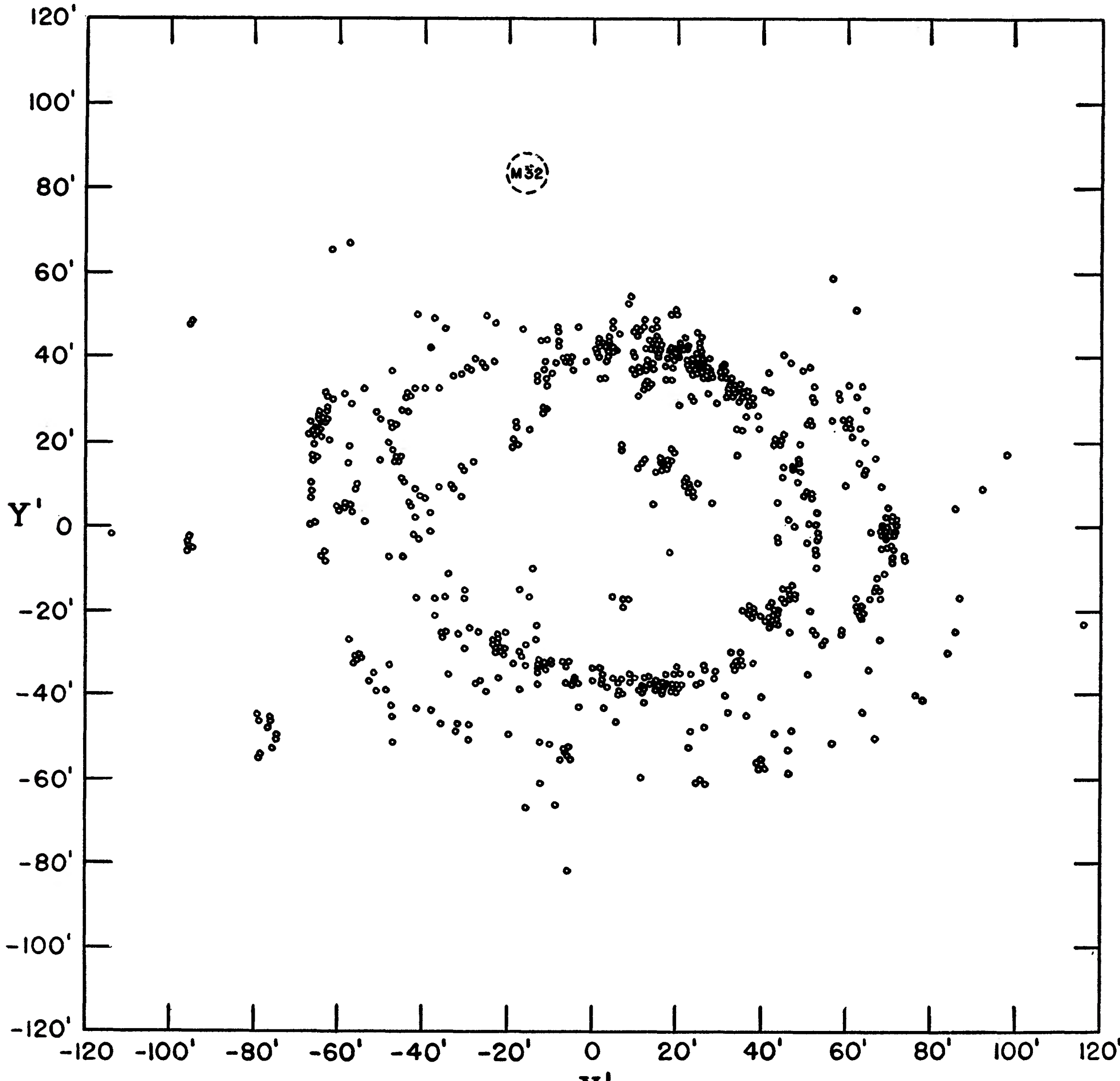

FIG. 5.—Plot of 688 emission nebulae with Y-coordinates multiplied by 3.6 (inclination $i = 16°$). M32 is located as it would appear if it were in or near the plane of M31.

nebulae arms coincide with the schematic spiral arms which were defined by the stars. One of the strongest, best-defined segments of emission nebulae, however, directly joins two adjacent arms (N4 to N3 at about $X = 20'$, $Y = -35'$). This is what gives the emission nebulae the appearance of rings rather than spirals and what causes us to look for other, more acceptable interpretations of the emission nebula pattern.

b) *Large Emission Nebulae*

In order to check the observational validity of the above-mentioned connection between adjacent arms, a list of large emission nebulae only was prepared from Table 1 of the preceding paper. This list contained 106 objects which were noted as large or measurable in the remarks to the table. These large emission nebulae confirmed very well the pattern exhibited by the total number of emission nebulae taken together. In general, it turned out that wherever there are numerous small nebulae there are some large nebulae.

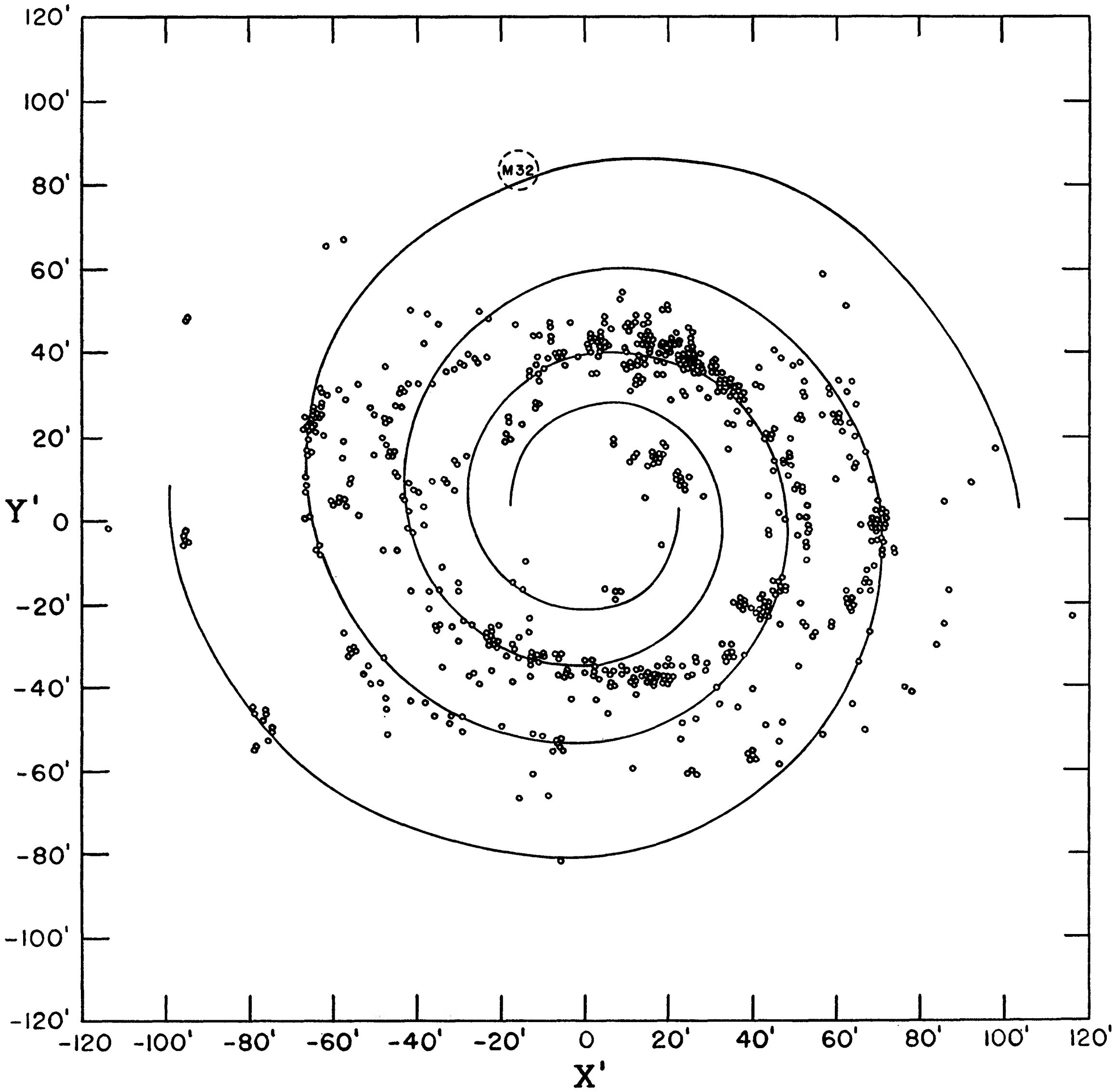

FIG. 6.—Emission nebulae of Fig. 5 with schematic log spiral $r = 30'e^{0.13\theta}$ fitted to the points

Working with this reduced list of nebulae, it was found by trial and error that another possible fit was obtained when the projection factor was increased to 5.2 ($i = 11°$) and the position angle of the major axis rotated 3° east through north in the unrectified image (clockwise in the orientations shown here). This rotation is necessary because the slope of the rectified emission nebulae arms as they sweep across our line of sight to M13 (near $X = 0$) is very sensitive to the adopted position angle of the unrectified major axis. A change to 36° position angle makes the pitch of the arms too flat near $X = 0$, and a change to 34° makes the pitch noticeably too steep. In order to make the emission nebulae arms agree with the schematic arms in the $X = 0$ region, particularly the most conspicuous N4 arm, the major axis must be adopted as 35° ± 1°. The 106 large nebulae are listed in Table 1, where their original X- and Y-coordinates have been rotated 3° clockwise and the Y's multiplied by a factor of 5.2. The entire list of 688 nebulae in Table 1 of the preceding paper was then transformed by the same rotation and projection factor and plotted in Figure 7. In Figure 8 the adopted spiral schematic is fitted to the plot of these points.

c) *Rectifying for Smaller Inclination Angles*

The larger projection factor of 5.2 ($i = 11°$) used to construct Figure 7 shows that the emission nebulae pattern is now of nearly equal extent in X and Y. If it is assumed that the emission nebulae all lie in a plane and are roughly circularly distributed, then this low an inclination angle will be derived. This is the interpretation on which Baade (1958) based his value of $i = 12°$ for the Andromeda Nebulae. Moreover, Figure 8 shows that the over-all fit of the emission nebulae to the schematic arms is also good. The major emission nebula arm can now be made to coincide with the major star arm in Figure 3 (N4). In two regions, however, other adjacent arms seem now to be connected together. The $X = 30$, $Y = 60$ part of the N5 arm seems to be connected to the N4 arm as it crosses the $Y = 0$ axis, and on the other side a connection is incomplete, but indicated, between the $X = -50$, $Y = -70$ part of the S6 arm to the S5 arm as it crosses the $Y = 0$ axis. These interarm connections are not as strong as the one in the $i = 16°$ fit and, if they are considered as merely details of bifurcation and branching, then this could be accepted as an interpretation of the emission nebulae measures.

This last rectification for $i = 11°$, however, would abandon the assumption that there is a single plane in M31 and would require that emission nebulae actually have a somewhat different plane than do the star arms. Also the rotation of the position angle of the major axis would be unexplained (see Appendix for further comments). Instead I would like to suggest a picture which combines advantages of both interpretations (*a*) and (*c*) and also agrees with the visual impression of M31.

d) *Warping of M31 Plane*

Figure 6 shows that the positive Y (far side of M31) emission nebulae are fitted very well with an inclination angle of $i = 16°$. Still referring to that figure, we see as we go around the spiral in a clockwise direction that at about 20° past the $Y = 0$ axis, the two major emission nebulae arms start to need an increasing rectification factor in order to keep the emission nebulae on a spiral pattern. Figure 8 shows that as these arms sweep across our line of sight on the near side of M31 they fit the spiral pattern well with a rectification factor of 5.2 ($i = 11°$). A straightforward interpretation of this is that the plane of M31 actually does warp from $i = 16°$ to $i = 11°$ in the near-side regions discussed above.

Confirmation of this interpretation can be obtained from the Hα picture of M31 shown in Figure 9. The near-side dust arms are better silhouetted against the red background than in normal pictures and the visual impression of warping of the preceding near-side arms is clearer. It is also seen from Figure 3 that the star arms in M31, just before they start to pass in front of the line of sight on the near side, start to need higher rectification

TABLE 1

POSITIONS OF LARGE EMISSION NEBULAE

$X' = X \cos 3° - Y \sin 3°$
$Y' = X \sin 3° + Y \cos 3°$

X′	Y′	5.2 Y′	X′	Y′	5.2 Y′	X′	Y′	5.2 Y′	X′	Y′	5.2 Y′
+ 0.322	+11.349	+59.015	− 8.606	+10.184	+52.957	− 5.845	−14.865	−77.298	+ 0.800	−10.007	−52.036
1.019	11.909	61.927	− 8.996	11.762	61.162	− 7.100	−18.599	−96.715	3.140	− 9.543	−49.624
1.687	9.702	50.450	−10.977	7.135	37.102	−10.510	−10.034	−52.177	6.437	− 9.886	−51.272
3.182	11.300	58.760	−11.436	7.076	36.795	−11.362	− 9.869	−51.319	6.967	−10.457	−54.376
3.993	11.765	61.178	−11.787	7.161	37.237	−16.721	− 9.147	−47.564	7.949	− 9.578	−49.806
4.423	13.606	70.751	−12.244	9.507	49.436	−22.018	− 9.012	−46.862	14.590	− 9.614	−49.993
5.836	12.924	67.205	−23.686	9.452	49.150	−28.595	−15.515	−80.678	15.014	− 9.439	−49.083
9.393	11.626	60.455	−28.685	2.792	14.518	−29.611	− 6.388	−33.218	18.791	− 9.860	−51.272
9.640	10.646	55.359	−29.073	8.795	45.734	−29.496	− 9.526	−49.535	19.694	− 9.651	−50.185
9.659	13.200	68.640	−36.186	0.783	4.072	−31.175	−14.458	−75.182	20.384	− 9.424	−49.005
10.511	12.911	67.137	−38.422	11.656	60.611	−31.346	−15.079	−78.411	20.387	− 8.164	−42.453
10.895	10.933	56.852	−42.462	6.838	35.558	−35.041	− 8.920	−46.484	26.524	−15.209	−79.087
11.934	14.100	73.320	−45.040	5.335	27.742	−37.178	−14.089	−73.263	27.226	−11.768	−61.194
12.434	9.910	51.532	−47.229	+ 2.868	+14.914	−75.358	−17.183	−89.352	34.313	− 7.435	−38.662
14.438	12.796	66.539	−56.733	− 0.375	− 1.950				35.338	− 7.077	−36.880
14.696	12.810	66.612	−63.689	+ 4.541	+23.613				37.885	− 3.742	−19.458
17.735	12.190	63.388	−64.254	+ 3.780	+19.656				40.753	− 4.238	−22.038
19.572	11.941	62.093	−64.713	+ 3.371	+17.529				41.630	−13.456	−69.971
19.675	12.339	64.163	−64.906	+ 3.521	+18.309				41.820	− 4.289	−22.303
21.123	12.495	64.974	−65.196	+ 3.248	+16.890				42.385	− 3.774	−19.625
23.560	11.738	61.038	−66.023	+ 1.014	+ 5.273				44.008	+ 1.376	+ 7.155
25.073	12.689	65.983	−66.344	+ 1.953	+10.156				44.074	+ 1.458	+ 7.582
26.805	11.587	60.252	−66.344	− 1.691	− 8.793				52.950	+ 0.922	+ 4.794
30.270	11.310	58.812	−66.672	− 1.291	− 6.713				55.462	− 4.796	−24.939
33.075	10.531	54.761							59.113	− 4.059	−21.107
34.079	10.658	55.422							59.455	− 3.804	−19.781
34.153	9.783	50.872							65.664	− 2.341	−12.173
35.573	10.239	53.243							66.201	− 6.000	−31.200
44.815	8.393	43.644							69.902	+ 3.309	+17.207
45.988	8.815	45.838							70.273	+ 3.126	+16.255
51.669	4.511	23.457							70.717	+ 2.326	+12.095
59.547	9.665	50.258							71.508	+ 1.443	+ 7.504
60.172	9.701	50.445							74.095	+ 1.648	+ 8.570
64.169	6.868	35.714									
52.170	11.109	57.767									

factors. The star arms at about this point become untraceable, and it is probable that the smaller inclination is what obscures them at this point.

It is just the transition from the inclination angle $i = 16°$ to $i = 11°$ which is capable of changing the rectified slope of the major emission arms on the near side to agree with a continuous spiral. Of course, it is not clear whether the near-side disk is folded like a plane relative to the far side, or whether the outer disk is raised up to form a high rim on the one side. In either case, however, the rotation of the apparent position angle of the major axis of M31, which we had to perform in Figure 8 to fit the near-side emission nebulae for $i = 11°$, is probably fictitious and is just a mathematical way of mimicking the change in spiral-arm slope which the changing projection factor from $i = 16°$ to $i = 11°$ would give naturally. Finally, as the near-side disk crosses back over the major axis in the direction of M32 ($Y = 0$, X negative), there is some indication that even

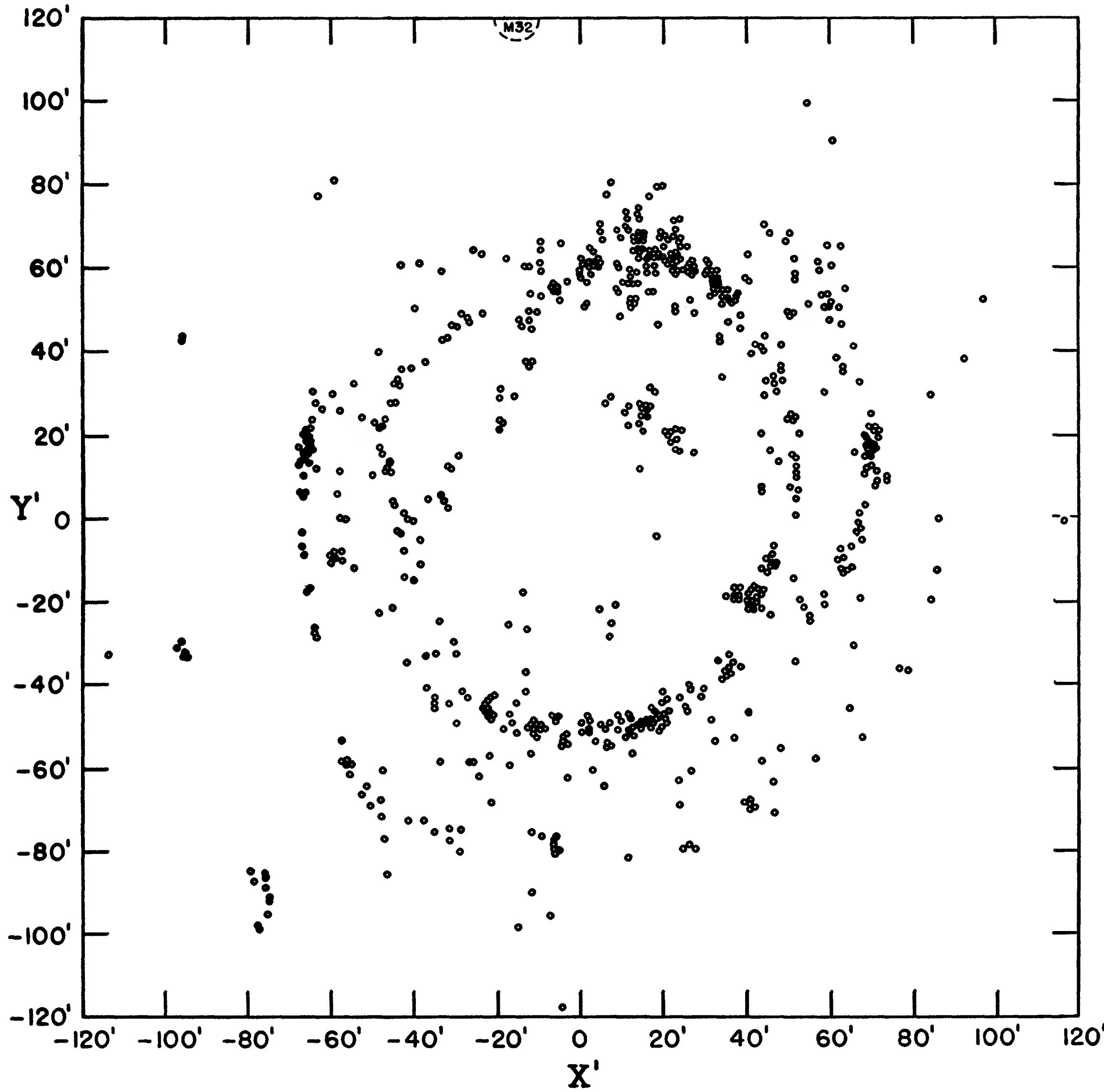

FIG. 7.—Plot of 688 emission nebulae with Y-coordinates multiplied by 5.2 (inclination $i = 11°$) and position angle of major axis rotated 3° to 35°. M32 is located as it would appear if it were in or near the plane of M31.

greater rectification factors are needed, but the warped plane changes its aspect relative to the line of sight very rapidly and the projection factors must also change sharply, making it difficult to reconstruct the exact behavior in that region.

e) The Angle of Inclination of M31

It has been suggested here that the major body of M31 has an inclination of around $i = 16°$, and that essentially just arms 3, 4, and 5 are inclined at the lower inclination of $i = 11°$ and only in the sector from the preceding side around to M32 on the south-preceding and south side. It was pointed out that this seems to be substantiated by the photograph in Figure 9, which shows all the inner features to run more in line with the north-following outer features which are on the side opposite M32, and therefore makes it appear as if only the outer edge, underneath M32, were raised above the $i = 16°$ plane.

Schmidt (1957) pointed out that a contradiction existed in that the flattening of the

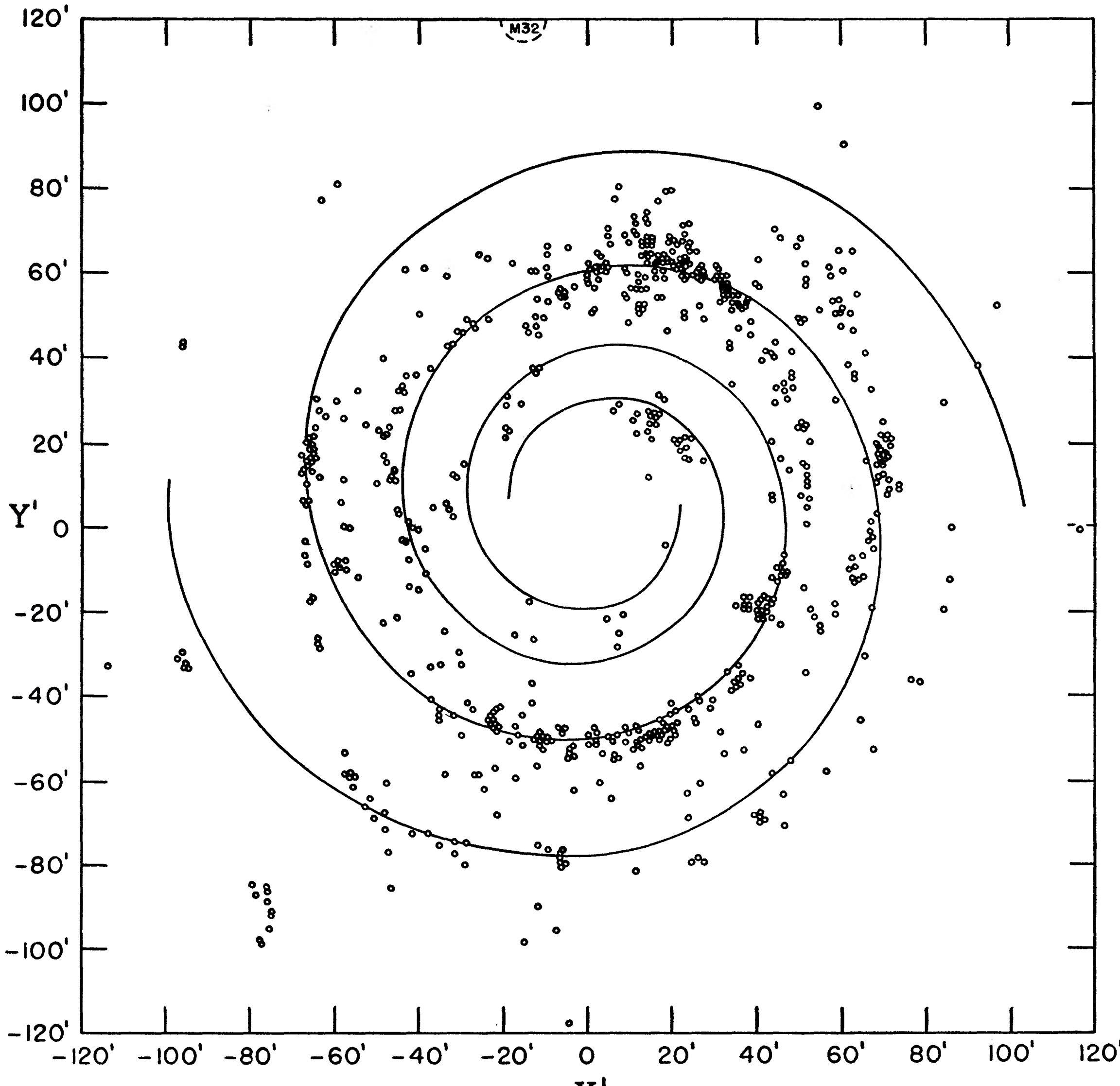

FIG. 8.—Emission nebulae of Fig. 7 with schematic log spiral $r = 30'e^{0.13\theta}$ fitted to the points

M31 luminous isophotes is not consistent with a low inclination angle near $i = 12°$ but rather requires $i = 16°$ or thereabouts. Wyse and Mayall (1942) observed the true ratio of minor to major axis (q) for Sb spirals to be between 0.07 and 0.09. A $q = 0.08$ is not large enough to make any sensible change in the derived true inclination of M31. The light isophotes from de Vaucouleurs' (1958) data therefore indicate a minimum inclination of $i = 15°$. If we were to adopt $i = 11°$ for the true inclination of M31, then we would need a true flattening of M31 near $q = 0.2$ to give the observed isophote ratios. At a radius $a = 9$ kpc, $q = b/a = 0.2$ would yield $b = 2$ kpc. We would have to conclude that luminous star arms were pulled out of this $i = 11°$ plane by about 2 kpc. In view of the perturbation by M32, such a possibility exists, but we would then be faced with extensively different planes for the emission nebulae and luminous matter. Therefore, the original interpretation of a single, warped plane will be retained here since it is consistent with the inclination given from the luminous isophotes and yet also explains the projected shape of the emission nebulae.

f) Perturbation by M32

In the photographic projection of Figure 4 it is clear that M32 appears projected close to the end of a major spiral arm. This is also true in the schematics of Figures 6 and 8, where there actually are a few emission nebulae which appear to lead toward M32.

Of course, M32 actually may lie considerably out of the plane of M31 and only by coincidence appear projected onto the end of a spiral arm. There is, however, growing evidence for the existence of a class of galaxies consisting of a spiral with an elliptical or dwarf elliptical attached to the end of a spiral arm (Vorontsov-Velyaminov 1959; Arp 1963). Those interactions seem to be plasma-magnetic in nature and, if M31 and M32 belong to this class of objects, the action of M32 on M31 may be directly through the gas arm rather than purely gravitational. In that case there would be some clue as to why the arm, and possibly the disk also in that particular region, are lifted slightly out of the plane for a quarter- to a half-turn ahead.

An important set of 21-cm radio observations has recently been completed by the Carnegie Institution of Washington (Burke 1963). The investigation shows that the gas and star arms are coincident on the north-following side of M31, but that the gas arms are displaced by about a kiloparsec or so from the star arms on the south-preceding side, near M32. Displacements of 1 or 2 kpc of the gas from the stars in $\frac{1}{4}$ revolution ($\frac{1}{4}$ revolution so that only one section of M31 is perturbed) need velocities of 50–100 km/sec of gas relative to stars. It would seem difficult for M32 to cause this by a gravitational perturbation. A magnetic pull affecting only the gas, however, might accelerate the gas relative to the stars. Discussion of this problem is not within the purview of the present paper, but it can be pointed out that the magnetic-plasma approach has possible application to both the warping of the plane and the separation of stars and gas.

A further question arises as to which objects the emission nebulae follow if there is a separation of young stars and gas in the vicinity of M32. It is clear from Figures 3, 5, and 7 that in some parts of M31 the star and emission nebulae arms are present simultaneously; in other parts one will be present more or less without the other. It is really the inability to trace star arms completely around M31 and the clumpiness of the emission nebula segments that preclude the possibility of deciding for certain if some of the emission nebulae arms diverge from the star arms in our projected view of M31.

Figure 10 is included here to show an example of a galaxy which has been perturbed by a dwarf elliptical companion. Although in both the M31 and NGC 772 cases the companions are about the same relative size, NGC 772 has been much more violently affected than in the case of M31. It is also interesting to note how the character of the arms changes from arms containing stellar knots to diffuse arms in Figure 10 as one proceeds toward the perturbing galaxy. Evidently the perturbation is such as to disturb the normal relationship between gas, dust, and stars in the spiral arms.

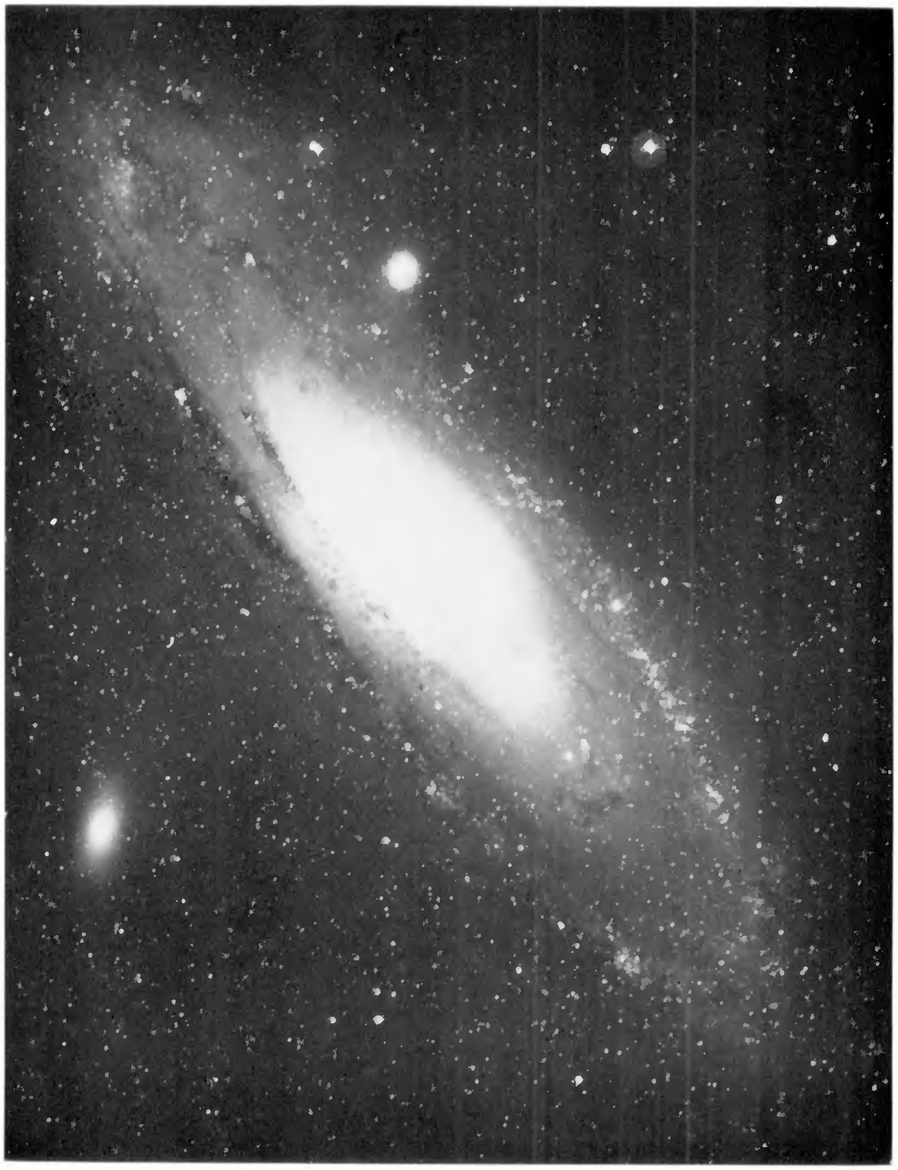

FIG. 9.—A photograph taken with the 48-inch Schmidt telescope through an Hα interference filter of 80 Å half-width. The emission nebulae show best the apparent warping-up of the plane from the near side around to M32.

FIG. 10.—A blue-sensitive photograph of NGC 772 showing a dwarf elliptical about the size of M32 which has caused a much greater perturbation on its parent galaxy. Note particularly the differences in appearance of the various spiral arms from one another, presumably a result of the perturbation.

APPENDIX

EFFECT OF THE PITCH OF THE SPIRAL ARMS ON THE POSITION ANGLE OF THE MAJOR AXIS

Baade adopted a major axis from the outermost spiral arms at 37°.7 (preceding paper). From outermost light isophotes, de Vaucouleurs (1958) derives an identical value of 37°.7. The position angle of the major axis of M31, however, is not constant. On the south-preceding side of the nucleus the axis appears tipped toward M32, particularly in regions from $X = -40'$ to $-60'$. If the outermost isophotes are ignored, as in a visual estimate, more weight is given to the perturbation by M32. Presumably this is why Hubble (1929) gives 36°.7. A visual estimate of the position angle in Figure 1 gives 36°.5 (parallel to the frame of the picture). Since the major rings of the emission nebulae at $X = -45'$ and $-60'$ pass directly under M32, it is possible that the emission nebulae system has the even smaller position angle of $35° \pm 1°$. This would require an actual physical tipping of this part of the disk relative to outer parts, however, and the apparent change in position angle has instead been interpreted in this paper as being primarily due to warping of the plane in the vicinity of M32.

Stock (1955) pointed out that the opening out of the spiral arms causes the apparent direction of the major axis to be rotated in the same direction. He used a pitch for M31 of $b = 0.2$ and a tilt of $i = 11°$, and computed that rotation in the unrectified image should be about 3°. Using the pitch found here of $b = 0.13$ and the same tilt, we could compute a rotation of about 1°.5. In Figure 1 the major axis defined by the principal arms is rotated about 2° from the position angle of the nebula as a whole, in the same sense predicted by Stock.

The innermost de Vaucouleurs' isophotes are at about position angle 42°. If this represents the true axis, and the outer isophotes are dominated by the spiral arms, then the real major axis could be apparently rotated toward the derived 37°.7 by the Stock effect, particularly if the pitch of the arms at that point is steep. But if, as found here, the pitch flattens further out, the apparent major axis should rotate back again. This last is not observed. Although qualitatively as predicted, it appears that the quantitative effect on the position angle of the major axis of the opening out of the spiral arms is uncertain in M31. It is presumed, however, to be generally around the 1°.5 computed here.

The purpose of noting this often-overlooked effect here is to point out that the real axis, if changed by this effect, would be changed in a sense to increase the discrepancy between it and position angle of 35° which it was necessary to adopt for the position of the axis of the emission nebulae for the $i = 11°$ case considered here.

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