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STELLAR MOTIONS NEAR THE NUCLEUS OF M31

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ABSTRACT

Velocities of stars along the major and minor axes in the nuclear bulge of M31 have been measured from the λ5269 Fraunhofer E absorption line (Fe I + Ca I). The mean uncertainty of each velocity is estimated to be 25 km s^{-1}. In general, the stellar velocities resemble the gas velocities which we have reported earlier. Along the major axis, the velocities rise steeply across the nucleus, and show a minimum at $R = 1600$ pc. Along the far minor axis, 300 pc $< R <$ 800 pc, excess positive velocities are observed in those regions where gas is observed streaming out from the nucleus. These regions of anomalous velocities appear to be coincident with spiral features. However, we can offer no realistic explanation of the complex stellar motions, or of their relation to the presumably younger gas.
Subject headings: galactic nuclei — galaxies, individual — galaxies, motions in

I. INTRODUCTION

In recent years, considerable progress has been made in studying the motions of the gaseous component in external galaxies. Velocities of the gas within a galaxy are measured with relatively high spatial and velocity resolution from spectroscopic studies of generally sharp emission lines. Velocities of neutral hydrogen are mapped with high accuracy from radio observations. The analogous problem, the study of the motions of the stellar component, has progressed much more slowly due to several factors. Most absorption features are broad and shallow and require longer exposures than do emission lines. Often they are blends (e.g., the G band) which arise from stars of various types with possibly differing spatial and velocity distributions, or single lines (H and K) broadened by the large velocity dispersion within the galaxy. In addition, the velocity resolution on the plate at the position of the H and K lines, in kilometers per second per micron, is only 0.6 times that which it is at the position of the Hα emission line. Finally, absorption lines arise from the integrated light of all stars along the line of sight, and the uncertain geometry of the stellar distribution complicates the analysis. For all of these reasons, velocities from absorption lines are generally of low accuracy. Consequently, there are very few studies which compare the velocities of the stars and the gas in a single galaxy.

We report here on a study of the velocities of the stellar component in the nuclear bulge of M31. From our study of emission lines in the nuclear disk of M31 (Rubin and Ford [hereafter RF] 1970, 1971) we have available a collection of spectra in the range 4600–7000 Å. The dispersion is 135 Å mm^{-1} at Hα, and the slit width corresponds to about 5 pc on the major axis of M31. In this spectral range we record one relatively sharp absorption feature, the Fraunhofer E line (a blend of Fe I and Ca I) at 5269 Å. At this wavelength, the scale factor on the plate is 8 km s^{-1} μ^{-1}. It was hoped at the outset that the knowledge gained from the study of the emission-line velocities would help in understanding the absorption-line velocities.

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Our earlier observations of the excited gas in the nuclear disk (RF 1971) were made at 28 Å mm^{-1}. At that dispersion, all emission lines are sharp (less than 60 km s^{-1} broad). This suggests that the nuclear gas, $R < 400$ pc, is concentrated into a very thin layer. The kinematical model which best reproduces the observed velocities in 16 position angles is a rotating disk, upon which are superposed more complex motions in some position angles. In two position angles about 180° apart,[1] there is a radial expansion of gas in the plane. Additionally, there are possible z-motions of gas clouds falling into the rotating disk. Whitehurst and Roberts (1972) have observed H I gas from the central region of M31 with velocities which also are explained by a model with a rotating disk, radial streaming in the plane, and z-motions. As we shall see below, the stellar velocities appear equally complex, although the observations are less complete.

II. THE OBSERVED VELOCITIES

At the time of the emission-line study, the E line was measured on several plates, using a Mann two-coordinate measuring machine, and these results were reported briefly (RF 1970). For the present more comprehensive study, all plates covering the nuclear disk of M31 were examined for absorption features. On plates at 135 Å mm^{-1} the sharpest absorption feature was the E line; plates at higher dispersion did not cover this spectral region, and no usable absorption lines were found on those plates. We show in figure 1 a reproduction of a plate showing the E line. In an effort to obtain the highest velocity accuracy, all plates on which the line was judged to be of good quality were measured on a Grant profile comparator. On portions of the line which are asymmetrical, two settings were made, one setting on the peak and a second setting midway between the shoulders. Measurements were made along the line every 0.3 mm on the plate, corresponding to 10″ on the sky, or 33 pc along the major axis of M31. A slit curvature plate, with the comparison lines across the entire spectrum, was also measured at the Grant instrument and used to correct for curvature of the lines. In an attempt to eliminate all association with the previously measured emission lines, there was no knowledge of the position angle θ or the location R covered by the spectrum during all measuring and reducing procedures. Only after all reductions were complete did we identify the regions over which absorption lines had been measured. Details of the plates are given in table 1. On several plates, absorption lines of Hβ and the Mg I triplet were measured, but these few measurements proved to be of no value.

To transform from the measured position of the absorption feature to a velocity, we must adopt a rest wavelength for the E line. This feature is prominent in solar- and later-type stars which contribute to the continuous spectrum near the nucleus of M31. We show in the Appendix that there is little likelihood that this line could be an interstellar (in M31) feature. For the Sun, the mean wavelength (weighted by equivalent width) is $\lambda_0 = 5268.9$ (Moore, Minnaert, and Houtgest, 1966). We have adopted $\lambda_0 = 5268.3$ for the blend at our dispersion. With this value, the observed velocities along the minor axis scatter about the systemic velocity ($V_0 = -300$ km s^{-1}), except for the expansion to be described later. The velocities observed along the major axis near the nucleus are the same as the nuclear gas velocities.

In table 2 we list the measured absorption line velocities. As indicated in the table, some values are the mean of two measured velocities at a single point, one velocity coming from the peak of the line and the second from the midpoint of the shoulders. The two velocities were generally within a few km s^{-1}. The remaining values are tabulated each 20″, although measurements were made each 10″. Means of two

[1] There is a misprint in the abstract of our earlier paper (RF 1971); the expansion is observed in P.A. 68°–128° and 248°–278°, not 68°–118° as printed.

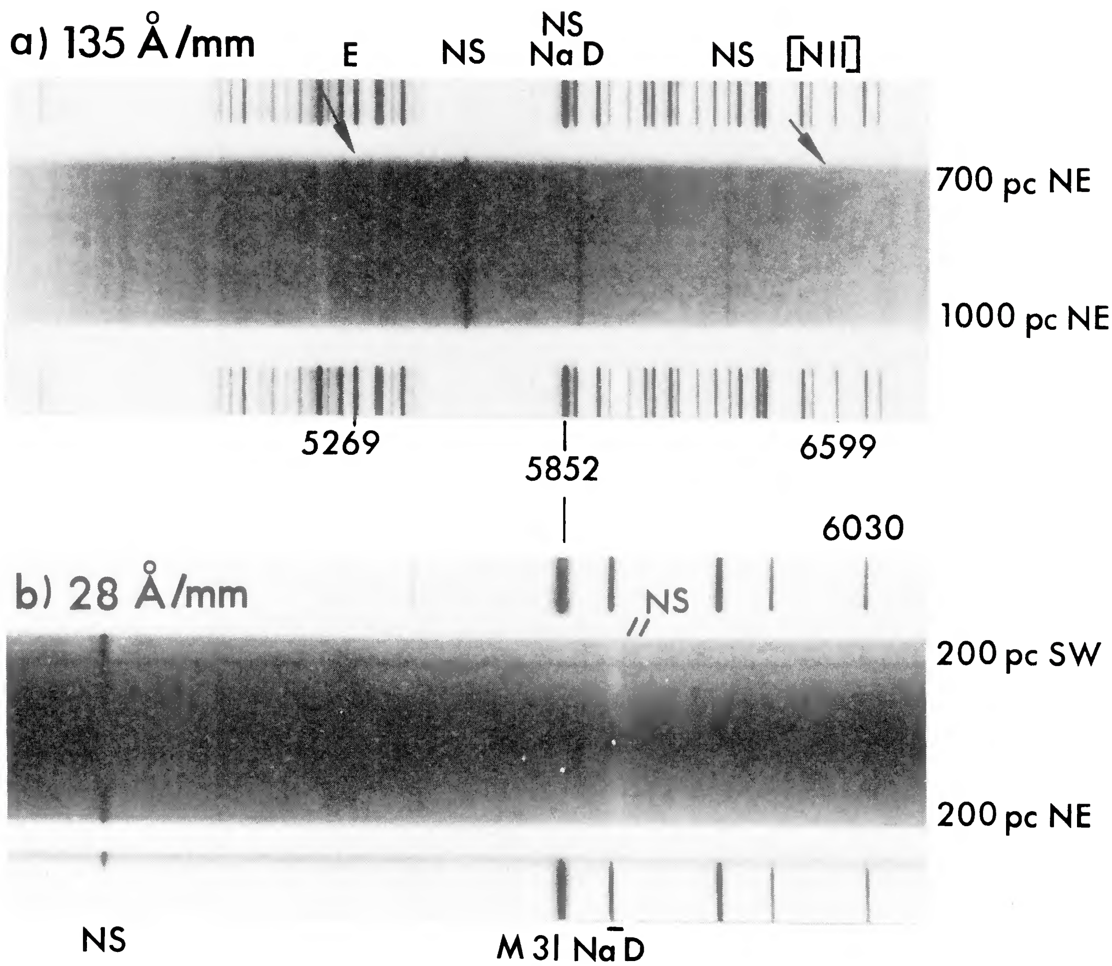

FIG. 1.—Spectra near the nucleus of M31. (*a*) Plate 1584, major axis about 4′ NE of nucleus, original dispersion 135 Å mm^{-1}, exposure 2^h. Arrows mark the position of the Fraunhofer E absorption line (λ5269) and the [N II] emission (λ6583). The Na D nightsky doublet, in emission, is barely resolved. (*b*) Plate 1793, major axis through nucleus, original dispersion 28 Å mm^{-1}, exposure 3^h53^m. The Na D nightsky doublet (λλ5290, 5296) is well resolved, while the blueshifted Na D absorption from M31 is broad and unresolved.

TABLE 1

M31 PLATES MEASURED FOR ABSORPTION-LINE VELOCITIES

Plate	Date (UT)	Exposure [min.]	r [arc sec from nucleus on sky]	Position Angle [degrees]
1575a	1968 Nov. 18	15	NE13–NE153	68
1575b	1968 Nov. 18	24	NE13–NE153	68
1578	1968 Nov. 18	169	NW75–NW110	128 Minor axis
1580d	1968 Nov. 19	10	NW31–SE49	128
1581	1968 Nov. 19	180	SE87–SE122	128
1584	1968 Nov. 19	120	NE202–NE297	38 Major axis
1591	1968 Nov. 20	20	SW20–NE39	38
1592	1968 Nov. 20	210	NE415–NE503	38
1593	1968 Nov. 20	229	SE147–SE234	128
1772	1969 Oct. 7	20	SW43–NE27	38
1773	1969 Oct. 7	60	SW70–SW136	38
1774	1969 Oct. 7	120	SW119–SW284	38
1775	1969 Oct. 7	234	SW394–SW487	38
1776	1969 Oct. 7	106	SW61–SW126	38

NOTE.—Dispersion for all plates = 135 Å mm^{-1}. No moon above horizon except: 1775, 26 day ☾ rose ~ 40 min before end of exposure, 140° from M31; 1776, 26 day ☾.

adjacent measurements are listed to introduce some small smoothing and reduce the table size.

It is necessary to establish the level of confidence in these values. There are three pairs of duplicate plates, 1591 and 1772 (major axis across the nucleus), 1773 and 1776 (major axis SW 2′), and 1575*a* and 1575*b* (P.A. 68°). Internal mean errors for each pair are 24, 24, and 22 km s^{-1}, respectively. In addition, for plates along the major axis, 1592, 1772, 1773, 1774, 1775, and 1776, the scatter from point to point was examined by calculating the difference for each two adjacent velocities. This procedure cannot satisfy the purist statistician, but it can indicate the size of the scatter. Actually, along the major axis the residuals will be composed of real gradients and random errors, so this procedure will overestimate the size of the internal errors. For these six plates, we find mean differences of two adjacent values of 24, 26, 34, 8, 28, and 27 km s^{-1}, with an overall mean of 24 km s^{-1}. Hence, we conclude that a realistic value of the internal errors is 25 km s^{-1}.

The resolution on the plates taken at 135 Å mm^{-1} is 5 Å, which corresponds to about 300 km s^{-1}. Thus, although we are satisfied that we can measure the central velocity of the absorption feature to within 25 km s^{-1}, we have no information from these plates concerning line widths (i.e., velocity dispersions) of less than 300 km s^{-1}. Measured absorption-line widths on these plates are generally near 300 or 350 km s^{-1}. However, we do have several plates at five times higher dispersion, 28 Å mm^{-1}, at the spectral region of the Na I D doublet (λ = 5890.0, 5895.9)[2], and we reproduce one of these in figure 1. As can be seen in comparison with the nightsky D emission lines which are sharp and well resolved, the M31 D lines are broad and unresolved on densitometer tracings. The large width of the lines arises not only from intrinsic velocity dispersion but also from integration along the line of sight, just as in the case of 21-cm H I observations in the plane of our Galaxy. We return to this point in § III. Minkowski's (1962) value of σ_v = 225 km s^{-1} for the velocity dispersion in M31 refers to regions within 10″ (33 pc) and hence closer to the nucleus than our velocities.

[2] These plates were taken to see if He I λ5876 could be detected in emission in the nuclear bulge. At this dispersion it was not seen. From our earlier measures of Hα surface brightness (RF 1971) we expect the line-to-continuum ratio at λ5876 to be about 0.04 for a He/H value of 0.1. This is below our detection capability.

TABLE 2

MEASURED ABSORPTION LINE VELOCITIES IN M31

Major Axis			Major Axis			Minor Axis		
Plate	R[1] min of arc on sky	V km/sec	Plate	R min of arc on sky	V km/sec	Plate	R[1] min of arc on sky	V km/sec
1775 SW	8.1	-431[2]	1772 SW	0.72	-353[2]	1593 SE	3.9	-285
	7.7	-332		0.40	-364		3.7	-246
	7.3	-345	SW	0.02	-241		3.6	-261
	7.0	-382	NE	0.37	-201		3.3	-391
	6.6	-394					3.2	-258
			1584 NE	3.4	-244[2]		3.0	-308
1774 SW	4.7	-328[2]		3.6	-181		2.7	-333
	4.4	-351		3.8	-179		2.6	-340
	4.1	-432		4.0	-181		2.4	-330
	3.7	-395		4.1	-226	mean	3.2	-298±11
	3.3	-472		4.4	-194			
				4.5	-253	1581 SE	1.9	-349
1773 SW	2.3	-471[2]		4.7	-205		1.7	-346
	2.0	-382		5.0	-156		1.4	-315
	1.6	-301				mean	1.7	-337±11
	1.2	-272	1592 NE	6.8	-244			
				7.2	-215	1580d SE	0.82	-162
1776 SW	2.3	-441[2]		7.7	-214		0.64	-199
	1.7	-307		8.0	-249		0.41	-249
	1.3	-357		8.4	-284		0.24	-324
	1.0	-361				SE	0.06	-341
						NW	0.17	-328
1591 SW	0.43	-389[3]					0.35	-236
	0.25	-410					0.52	-276
SW	0.02	-320				mean[4] SE	0.15	-301±20
NE	0.15	-237						
	0.33	-208				1578 NW	1.2	-315
	0.57	-161					1.6	-259
	0.73	-207					1.8	-290
						mean	1.6	-288±16

Notes: (1) 1'= 200 pc along major axis; 1' = 890 pc along minor axis for distance = 690 kpc.
(2) Mean of 2 adjacent measures (i.e. for R=8′.1, one at R=8′.0 and one at R=8′.2).
(3) Mean of 2 velocities, one from peak, one from shoulder of line profile, at same R.
(4) Mean of last 5 values; high velocities excluded.

A recent observation by Morton and Thuan (1972) has lowered the nuclear dispersion to 120 ± 30 km s^{-1}.

In figure 2 we have plotted the absorption-line velocities along the major axis, as a function of distance from the nucleus. With respect to the central velocity, the velocities rise steeply to 100 km s^{-1} within 100 pc of the nucleus, remain near 100 km s^{-1} at $R = 800$ pc, and decrease to about 50 km s^{-1} near $R = 1600$ pc.

The [N II] emission line velocities across the nuclear disk (RF 1970, 1971) are also shown in figure 2. In the region $0 < R < 400$ pc NE, emission line velocities from [O II] 3727 (Münch 1962) are in very close agreement with the [N II] values (RF 1971, fig. 2*a*). On the NE major axis, the steep rise across the nucleus in the emission-line velocities is seen in the absorption lines as well. At 800 pc NE, the absorption-line velocities are significantly lower than the emission-line velocities. On the SW major axis, both emission-line velocities and absorption-line velocities show a peculiar hump near $R = 250$ pc. The velocity minimum near $R = 1600$ pc was observed in the excited gas only along the NE major axis; no gas was detected on the SW major axis at this distance from the nucleus. The absorption-line velocities indicate a minimum in

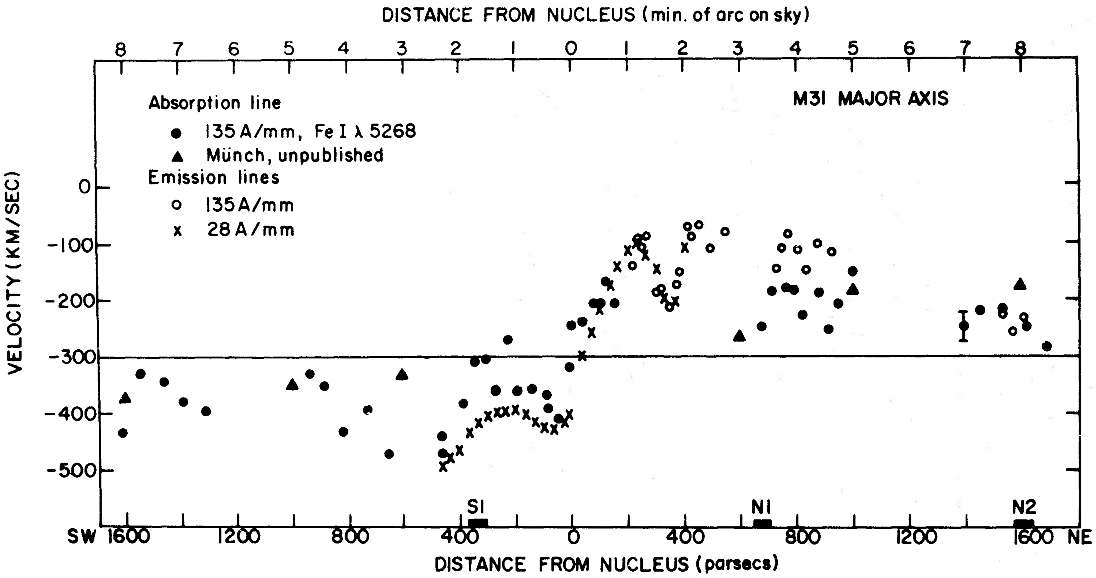

FIG. 2.—Stellar velocities along major axis near nucleus of M31, as a function of distance from the nucleus. Emission-line velocities are also shown. Note similarity of velocities of stars and gas near nucleus and near $R = 1600$ pc NE, and significantly lower stellar velocities at $R = 800$ pc. Unpublished absorption-line velocities from Münch are shown. Crossings of spiral arms (Baade 1963) are shown as S1, N1, N2.

the velocities near $R = 1600$ pc both NE and SW. This can be seen clearly in table 3 and figure 3, where we list mean velocities formed from table 2, and plot them along with the mean rotation curve for the nuclear disk of M31 determined from the excited gas (RF 1971). This minimum in the stellar velocities, which resembles the minimum in the gas velocities, is one of the most striking features we observe in the stellar motions.

A minimum in the stellar velocities near $R = 1600$ pc had been observed by Babcock (1939) from measures of the H and K lines across the nucleus of M31. With respect to the central velocity, the velocities he measured rise to 100 km s^{-1} at a distance of a few hundred parsecs, and fall to near zero at $R = 1600$ pc, both NE and SW. In their gross features, our absorption-line velocities confirm the earlier measurements of Babcock. Münch has also measured absorption lines in the blue spectral region along the major axis at $\pm 3'$, $\pm 5'$, and $\pm 8'$ from the nucleus of M31, and has

TABLE 3

MEAN VELOCITIES ALONG MAJOR AXIS IN M31

NE				SW			
$\bar{R}$ [pc]	$\bar{V}$ [km s^{-1}]	$\bar{V} + 300$ [km s^{-1}]	N	$\bar{R}$ [pc]	$\bar{V}$ [km s^{-1}]	$\bar{V} + 300$ [km s^{-1}]	N
57	-215 ± 11	85	3	19	-324 ± 49	24	3
130	-184 ± 13	116	2	130	-367 ± 8	67	4
				290	-309 ± 18	9	4
				440	-431 ± 29	131	3
740	-196 ± 16	104	4	740	-433 ± 22	133	3
908	-207 ± 16	93	5	910	-340 ± 12	40	2
1447	-224 ± 10	76	3	1360	-388 ± 6	88	2
1640	-266 ± 18	34	2	1540	-369 ± 31	69	3

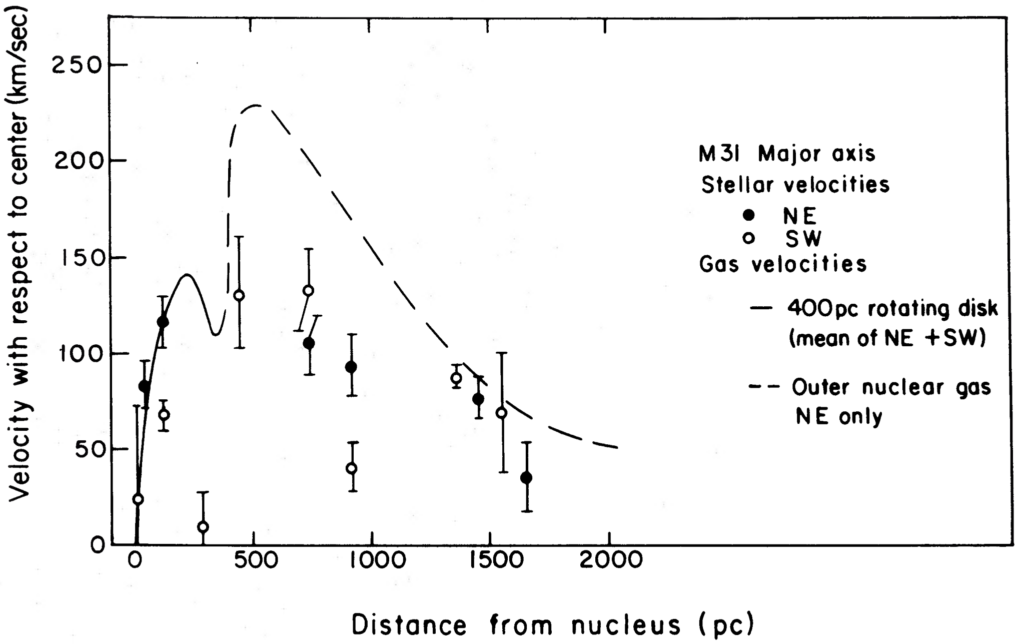

FIG. 3.—Mean stellar velocities along major axis of M31. Average gas velocities for 400 pc disk (RF 1971) and outer nuclear gas (NE major axis only) are also shown.

reported that the velocity minimum at 8′ does not exist (Münch 1964*a*, *b*). We plot in figure 2 the values which he kindly made available. The greatest discrepancy with our velocities is near 3′ SW, although we have no observations overlapping his. It appears that the complexity of the velocity field which we observe makes it unwise to draw a curve based only on a few points. Moreover, the innermost (dust) spiral arms cross near 3′ and undoubtedly add to the confusion here. This is discussed further in § III.

In P.A. 68°, the absorption-line velocities show the same steep velocity gradient that was seen in gas velocities (RF 1971). Along P.A. 128°, the minor axis, emission-line velocities of [O II] (Münch 1962) and [N II] (RF 1970, 1971) indicate that gas is leaving the nucleus on the SE (far side) minor axis, at distances from 300 pc $\leq R \leq$ 800 pc in the plane of the galaxy. The measured absorption line velocities are remarkably similar to the emission-line velocities, as shown in figure 4. Both emission- and absorption-line velocities scatter about the central velocity, with $V = -300$ km s^{-1}, except in the region 300 pc $< R <$ 800 pc, where positive velocities (with respect to the central velocity) are observed. The presence of motions along the minor axis for the stellar component which resemble the motions of the gaseous component are both unexpected and puzzling. Attempts to understand some facets of the problems posed by these observations are discussed below.

III. SOME ATTEMPTS AT UNDERSTANDING THE OBSERVATIONS

We have observed absorption lines near the nucleus of M31 which (1) show a large gradient of V with R within 100 pc of the nucleus, (2) have a velocity minimum near $R = 1600$ pc along the major axis, (3) are too positive along the far minor axis,[3] and

[3] If we were to adopt a longer wavelength for the mean wavelength for the E line, then the expansion along the minor axis would be observed both along the near and far sides. However, the average velocity for the other regions of the minor axis would be near $V = -350$ km s^{-1}, rather than $V = -300$ km s^{-1}, the observed central velocity. The major-axis observations would also be strangely asymmetrical. The velocity minimum at $R = 1600$ pc would still exist.

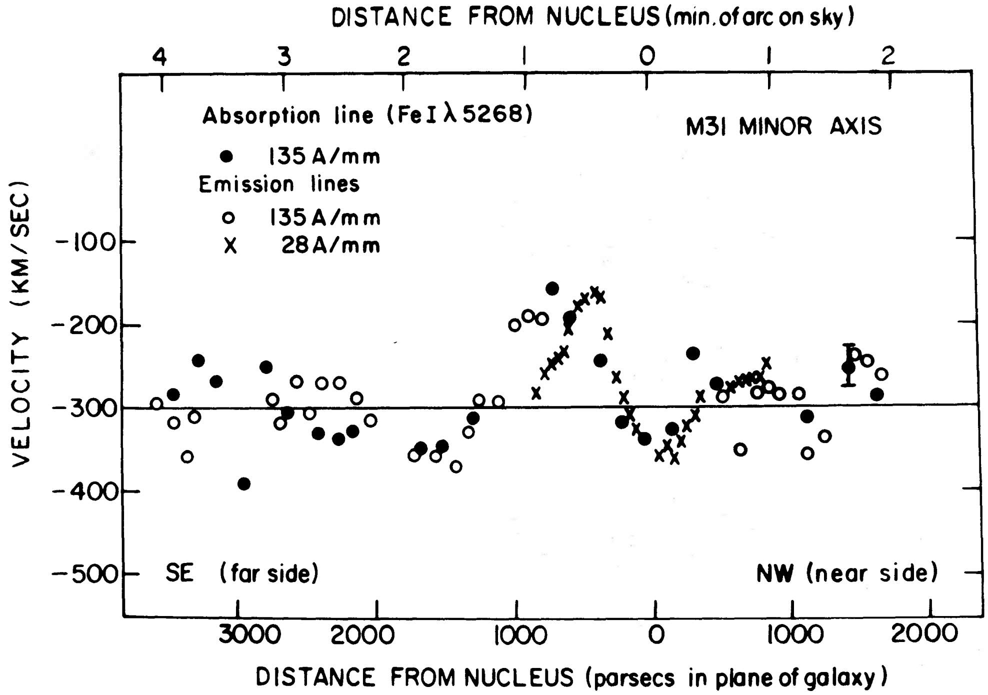

FIG. 4.—Stellar velocities along minor axis of M31, as a function of distance from the nucleus. Emission-line velocities are also shown. Note positive (with respect to center) gas and stellar velocities near 600 pc SE.

(4) overall, bear a remarkable resemblance to the velocities observed in the excited gas near the nucleus, but (5) by their width suggest that we are probably observing a spheroidal distribution of stars, rather than a disk as was the case for the gas.

The work of Spinrad and Taylor (1971; Spinrad 1971) and Faber (1971) indicates that near the nucleus of M31, in the spectral region near $\lambda = 5300$ Å, 96 percent of the light comes from only 2 percent (by mass) of the stars (i.e., $10^8 M_\odot$), stars of types G and K dwarfs (26 percent), G subgiants (20 percent), and super-metal-rich K giants (50 percent). From the G0–G8 turnoff the main sequence, an age of 4×10^9 years is obtained (Spinrad 1971) for a metal-rich population. This is consistent with van den Bergh's (1971) conclusion that the dominant stellar population in the nuclear bulge of our Galaxy consists of old metal-rich objects.

However, it is possible that the motions we observe are typical of much more of the nuclear population. This follows from observations by Sandage, Becklin, and Neugebauer (1969) which show that the distribution of 2.2-μ radiation within 100 pc of the nucleus of M31 is identical to that in the visual region. This makes it likely that the late-type stars, which are a major contributor to the light at 2.2 μ as well as the major contributor to the mass near the nucleus, have dynamical properties similar to those of the G- and K-type stars we observe. This has been discussed by Oort (1971).

Of the many questions raised by the stellar velocity observations, we will mention two which seem important. How can nuclear stars, with ages over 10^9 years, have motions which resemble motions of the gas, motions which are unlikely to exist more than some 10^6 or 10^7 years (RF 1971)? After considering many alternatives, a few of which are described below, we think it most likely that we are observing some part of complex orbital stellar motions, perhaps arising from gravitational asymmetries, which continue to keep the gas stirred. If this is gas recently ejected from stars evolving along the giant branch, then the similarity of motions follows directly. An alternative which appears less likely, that the stars we observe have ages $t \sim 10^7$ years, is discussed later.

The second question is how motions in a *spheroidal* stellar distribution can resemble those of a *flattened* gas disk. To investigate the effective sphericity of the stellar system, we have adopted the model of Kinman (1965) for the stellar density distribution near the nucleus of M31. This model, based on luminosity profiles in the blue, is valid for the visual spectral region, because the color variation near the nucleus is small (Sandage *et al.* 1969). We know that the stellar disk of M31 is transparent, because (1) telescope views show a sharply defined semistellar nucleus, not obscured by foreground stars, (2) velocity variations within a few parsecs of the nucleus can be detected (Lallemand, Duchesne, and Walker 1960), and (3) stellar disks near the nucleus of M31 cover only 10^{-10} of the available surface area (Sandage 1971).

A single point on the spectrum is formed from the integrated light of all stars along the line of sight. Because we view M31 only 13° to edge-on, there is a long path length through the galaxy for points along the major axis. For example, at $R = 800$ pc, the ellipticity of the stellar distribution is $c/a = 0.6$ (Kinman 1965). However, our calculations show that 70 percent of the light contribution at $R = 800$ pc comes from stars within $z = \pm 75$ pc of the plane. Hence the effective ellipticity is considerably flatter than the observed light distribution, thus reducing the problems posed by the similarities of the gas and stellar motions.

Along the minor axis, the geometry is different. For the point on the spectrum measured at $R = 800$ pc along the far minor axis, about 30 percent of the light contribution arises from stars within 75 pc of the plane, stars with distances ranging from about 500 to 1000 pc from the nucleus. An additional 50 percent of the light comes from stars with $75 < z < 200$ pc, the majority of which are located about 150 or 200 pc above the nucleus. Thus, while some 80 percent of the starlight contributing to the spectrum at $R = 800$ pc comes from stars within 200 pc of the plane, these stars range in distances from 0 to 1000 pc from the axis of rotation. These examples illustrate that even though the effective distribution of stars is significantly more flattened than the luminosity profiles indicate, the viewing angle complicates the interpretation. We present below some ideas which we have considered in an attempt to examine these questions.

a) *A Steady-State Kinematical Model*

To see if a steady-state kinematical model can be constructed, we have investigated a model in which the G- and K-type stars within 3000 pc of the nucleus are distributed in spheroids, moving in well-aligned orbits of moderate or small eccentricity, with rotational velocities which resemble the gas at the same distance R (and hence known from our earlier studies). Such might be the case, for example, if the gas had recently been shed by evolving stars. The density distribution and the geometry are taken from Kinman (1965). This model will account for the major features of the absorption-line velocities across the major axis. There will be a large velocity gradient across the nucleus, and the velocities observed at $R = 800$ pc will be displaced about 100 km s^{-1} below those observed in the gas. This displacement arises from the contribution to the absorption line from stars with $R > 800$ pc lying along the line of sight, whose projected velocities are less than the rotational velocity at $R = 800$ pc. For the gas, located in a very flat disk ($z \sim 25$ pc), no such degradation occurs, and the velocity observed at $R = 800$ pc is just the value given by the rotation curve. Additionally, only a rotation curve with a low velocity at $R = 1600$ pc will produce the low velocity observed in the excited gas. This is illustrated in figure 5.

Calculated absorption line profiles are shown in figure 5, for $R = 100$, 800, and 1600 pc along the major axis. The observed velocity at each distance is indicated by

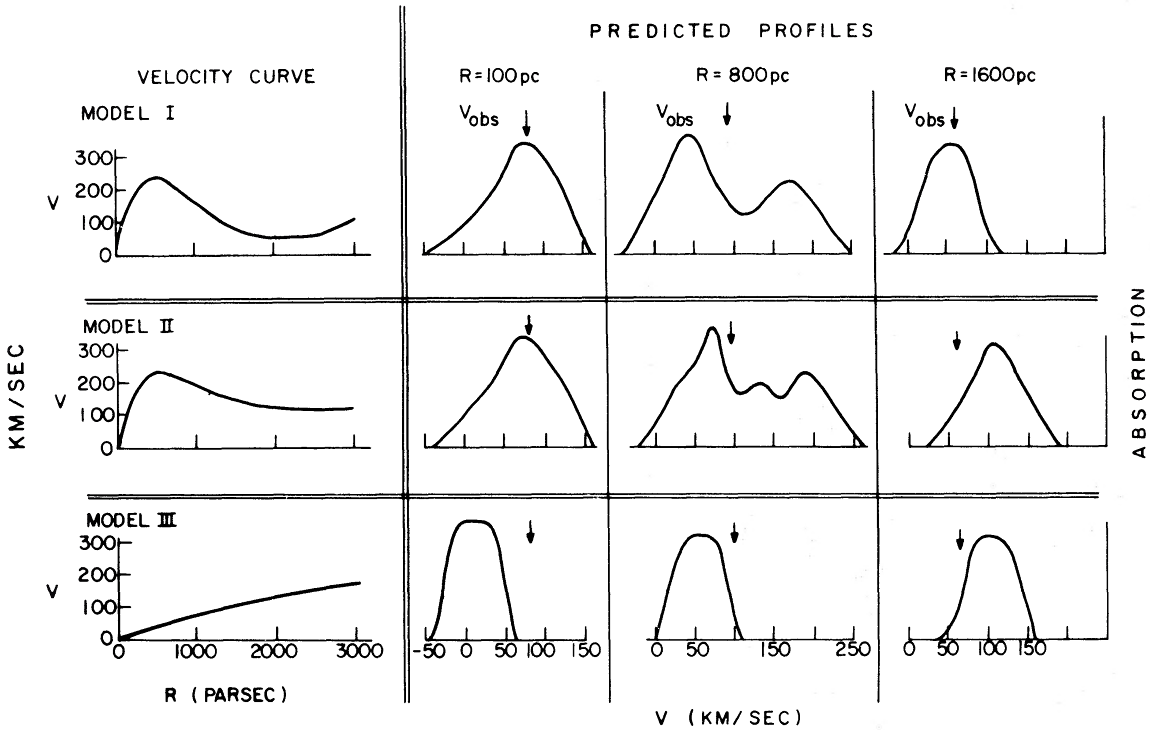

FIG. 5.—Calculated line profiles near nucleus of M31, for spheroidal stellar distribution and three velocity models shown at left. For three distances from nucleus, $R = 100$, 800, and 1600 pc, predicted velocities are compared with observed velocities, indicated by arrows.

an arrow. For velocity Models I and II, the midpoints of the computed profiles for $R = 100$ pc and 800 pc are close to the observed velocities; for Model III the calculated profiles are too negative. At $R = 1600$ pc, only Model I, the velocity curve with the low minimum, produces a profile which matches the low observed velocity.

The velocity agreement along the major axis notwithstanding, the model is unrealistic because it assumes orbits of small eccentricity, whereas large radial streaming is observed. Clearly, radial motions must be present, at least in some position angles. If stars are moving in elliptical orbits, we should observe inward radial motions in some positions. Our observations cover too few position angles to see whether inward motions exist.

The parameters calculated for stellar orbits (MacMillan 1930), with the adopted geometry and density distribution for M31, indicate that the stars are not leaving the nucleus; their velocities are well below the escape velocity. At $R = 700$ pc, the circular (gravitational) velocity is $V_{\rm circ} = 300$ km s^{-1}; the escape velocity is $V_{\rm es} = 450$ km s^{-1}. From our observations, a star at $R = 700$ pc could have $V_{\rm tan} = 200$ km s^{-1}, $V_{\rm rad} = 150$ km s^{-1}, or a total velocity in the plane of $V = 250$ km s^{-1}, well below the circular and escape velocities. A star with these velocity components will lose most of its kinetic energy in 10^6 years in moving radially outward only 100 pc. We have not investigated the outward effects on the orbits of a continuing mass loss from the nucleus, as would be the case if the nucleus of M31 is a source of gravitational radiation, as Weber (1970) has suggested for our Galaxy.

It would be satisfying to be able to understand the observed radial streaming near the nucleus of M31 in terms of the Lin, Yuan, and Shu (1969) density-wave theory, as Tully (1972) has done for gas motions near the nucleus of M51. Contopolous (1970*a*, *b*) has shown that at the inner Lindblad resonance, matter is confined into two elongated dispersion rings. However, such models require symmetry through 180°, while we observe a striking asymmetry between the near and the far minor axes in M31. Tully has shown that there are abrupt velocity discontinuities in M51 in regions where the dispersion ring meets the spiral arm. If we are observing some portions of elongated dispersion rings in M31, they are being additionally complicated by other velocity effects and the viewing angle.

The detailed picture of the spiral pattern close to the nucleus of M31 remains unknown. Baade (1963) placed the north crossings of the two inner arms at $N_1 =$ 680 pc, $N_2 =$ 1600 pc on the NE major axis, and the south crossings at $S_1 =$ 340 pc and $S_2 =$ 2100 pc; more details were not specified. Baade wrote "N_2 connects with S_2, N_3 connects with S_3," etc., but he was uncertain if S_1 and N_1 were crossings of the same arm.[4] However, if S_1 and N_1 are connected such that the arm trails, then it crosses the far minor axis near $R =$ 500 pc, in the region where outward motions are seen. The complex dust pattern there may be seen from photographs by Baade (RF 1971, fig. 8) and Johnson and Hanna (1972).

The variation of surface brightness along the minor axis this close to the nucleus is virtually unstudied. The only measurements of which we are aware are by Sandage *et al.* (1969) for four points; 48″ SE, 24″ SE, 24″ NW, 48″ NW. Detailed luminosity studies are needed to see if the anomalies in the velocities are accompanied by fluctuations in the surface brightness. There are recent high-resolution observations near the nucleus of M31 at 1415 MHz with the Westerbork interferometer (van der Kruit 1972) which show two point sources near the nucleus. These are located (if in the plane) at distances of 300 and 1000 pc from the nucleus, in position angle only 5° from the far minor axis where we observe the outward motions. These are probably giant H II regions, as van der Kruit suggests, which may be related to the strange velocity patterns observed there.

A second well-established coincidence exists at $R =$ 1600 pc, where the N_2 arm crosses the north major axis just at the minimum in the observed velocities. These facts suggest that the peculiarities which we observe in the velocity field of both the stars and the gas may be related in some unknown way to the asymmetrical spiral pattern near the nucleus of M31. While the arms probably do not contain sufficient mass to distort the stellar orbits gravitationally, resonance or other cooperative phenomena may be effective. In M31, because of the complexity of the velocity asymmetry and because the geometry of the spiral structure is obscured by the viewing angle, we have not attempted to make detailed comparisons with models based on the density wave theory. Our own prejudice is that we are most likely observing some portion of a complex orbital motion, which is unclear due to our limited velocity material and the geometrical effects involved in the viewing angle.

b) *Short-lived Models*

There are alternatives to the steady-state models. Gas could have been expelled from the nucleus some 10^7 years ago at an angle to the plane, and fallen back to the plane, perhaps near $R =$ 1600 pc, where its interaction with the disk gas would cause it to slow down and move radially outward. For our Galaxy, orbits for such clouds ejected from the nucleus have been studied by van der Kruit (1970). Initial velocities as large as 600 km s^{-1} are required to eject the gas a few kiloparsecs from the nucleus.

While this explosive origin could account for the complex motions we observe in the gas, it can explain the stellar motions only if the stars were formed after the gas had fallen back to the plane. This requires that (1) the stars whose G- and K-type spectra we presently observe are very young stars, and (2) normal evolved G and K stars do not contribute to the spectrum in the regions of anomalous velocities. We have in-

[4] Note that the spiral pattern for M31 published by Arp (1964) does not follow this recipe.

vestigated this possibility, first suggested to us by Professor Oort, but can find little to support young ages for these stars. Of conventional Population I metal-rich G or K dwarfs, giants, and supergiants, only supergiants evolve so rapidly that they could have evolved off the main sequence and still be only 10^7 years old (Iben 1967). However, there is substantial evidence that no supergiants exist in the nuclear population of M31. For the composite spectra of the nucleus of M31 synthesized by Spinrad (1971), the best fit $\lambda < 4500$ Å occurs when there are no upper-main-sequence O and B stars, nor any stars hotter than a few late F dwarfs. Hence, the late-type supergiants, which are less populous than the blue supergiants by perhaps a factor of 10 (Lucke 1972), are essentially absent (so much so that they are never considered by Spinrad). Even a massive 5 $M_{\odot}$ giant evolves too slowly ($t \sim 7 \times 10^7$ years) to reach the K giant branch in 10^7 years. The remaining possibility is that the giants we observe are very young stars still contracting to the main sequence. Large-mass stars ($M > 3\ M_{\odot}$) pass through the red and yellow giant region in less than some 10^5 years (Iben 1965) in contracting to the main sequence. Because of the short life-span of giants, it is statistically unlikely that massive young stars could contribute the 50 percent of the luminosity at $\lambda = 5300$ Å attributed to G–K giants. We are forced to conclude that supergiants are absent and giants are old.

The situation is different for stars near 1 $M_{\odot}$. Contraction times for these stars is near 10^7 years. We could be observing stars whose formation was initiated 10^7 years ago at the shock front between the colliding gases. These stars would share the motions of the gas from which they were formed. Additional gas could also come from the contracting stars, which eject a significant portion of their mass during contraction (Kuhi 1964). However, if the present dwarfs are contracting, the upper main sequence should be populated with more massive stars born at the same time. In our Galaxy, contracting stars (T Tauri stars) are only known in regions of high O and B star density (Herbig 1962). In M31, conditions at the initiation of star formation would have had to preclude the formation of massive stars.

Even if we are willing to accept these conditions and adopt young ages for the dwarfs, there still remains 70 percent of the observed nuclear stellar population which cannot be this young. Moreover, we have no adequate explanation for the absence of evolved G and K dwarfs in the regions of anomalous velocity. Admittedly, we know little about the evolution of stars in the crowded environment of the nucleus of a galaxy. Yet to have a majority of *young* G- and K-type stars would require that we are totally misinterpreting the stellar populations whose integrated properties we are observing.

IV. CONCLUSIONS

A complex pattern of motions for the G- and K-type stars in the nuclear bulge of M31 has been observed, which closely resembles the motions in the excited gas studied earlier (RF 1971). Both rotational and streaming motions are seen. We can offer no realistic explanation of the stellar motions, or of their relation to the presumably younger gas; nor can we justify the assumption that we are observing young stars with G- and K-type spectra. In our own Galaxy, a highly complex pattern of rotational and radial motions is observed near the nucleus, both at 21 cm (Rougoor and Oort 1960; Kerr 1969; van der Kruit 1970; Sanders, Wrixon, and Penzias 1972) and for discrete clouds of OH, H_2CO, and other molecules (McGee 1970; Scoville 1972; Scoville, Solomon, and Thaddeus 1972; Kaifer, Kato, and Iguchi 1972). Hence, it is perhaps not surprising that observations in just two position angles in M31 do not enable us to understand the velocity pattern there.

Finally, it should be emphasized that the main purpose of this paper has been to present the absorption-line velocities. We cannot adequately interpret the stellar motions. The models we have mentioned are meant only as a first look at the peculiarities of the nuclear region. We recognize the very high probability that considerations of fundamental importance in governing the motions of stars near the nucleus of M31 have not been mentioned above. Ambartsumian (1958, 1965) has long advocated that unknown phenomena are taking place in nuclei of galaxies. He has recently (1971) written, "Nature is endlessly more complicated and diverse than it seems to us, who until recently had no information of these wonderful processes. Let us study them with patience and base our conclusions mainly on the observational data."

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APPENDIX

CAN THE E-LINE BE INTERSTELLAR (IN M31)?

In table A1 we list those lines in the solar spectrum between 5266 and 5272 Å for which the equivalent width W is greater than 25 mÅ. The line identification list for the planetary nebula NGC 7027 (Bowen, Aller, and Minkowski 1955) has no strong permitted lines between 5266 and 5272 Å. The most important line for our consideration is the Fe I line (a^5F_5–$Z^5D^o{}_4$) at 5269.54 which is the strongest component of the E-line. We assume that the interstellar gas in the nucleus of M31 will affect the absorption line velocities if its contribution to the equivalent width is 100 mÅ or greater. This requires that there be at least 1.0×10^{14} atoms per cm^2 of Fe I in the $a^5F^o{}_5$ state along the line of sight. The f-value for the transition is 4×10^{-3} (Corliss and Tech 1968).[5] Let us assume that the required aerial density of Fe I is present and examine the observational consequences.

The a^5F_5 state can decay to the ground state (a^5D_4) of Fe I emitting an infrared line at 1.443 μ with a transition probability 2×10^{-3} s^{-1} (Grevasse, Nussbaumer, and

TABLE A1

COMPONENTS OF THE E-LINE IN THE SOLAR SPECTRUM

Wavelength [Å]	Ion	Lower Energy Level [eV]	$W_\odot$ [mÅ]
5266.56..........	Fe I	3.0	250
5267.28..........	Fe I	4.37	25
5268.34..........	Ni I	4.54	37
5268.61..........	Ti I	2.60	28
5269.55..........	Fe I	0.86	478
5270.27..........	Ca I	2.52}	255
5270.38..........	Fe I	1.61}	

[5] The recent redetermination of the f-values for Fe I transitions (Bridges and Wiese 1970) does not include this line; however, it is unlikely to be in error by more than 30 percent. This is not critical for our order-of-magnitude calculation.

TABLE A2

ATOMIC PARAMETERS FOR O I AND Fe I

Atom	Level Upper	Level Lower	A_{21} [s^{-1}]	$q_{21} \times 10^9$ [$cm^6\ s^{-1}$]
Fe I.......	$^5D_4$	a^5F_5	2×10^{-3}	30
O I........	$^1D_2$	$^3P_2$	5×10^{-3}	2

Swings 1971). In our case the surface brightness of the line will be 2.4×10^{-2} ergs $cm^{-2}\ s^{-1}\ sterad^{-1}$, which is to be compared with the neighboring continuum brightness, 10^{-4} ergs $cm^{-2}\ s^{-1}\ sterad^{-1}\ Å^{-1}$ (Sandage *et al.* 1969). Because the observed emission-line widths (RF 1971) correspond to turbulent velocities less than 70 km s^{-1}, it is clear that the forbidden infrared line should be easily detectable. This is true, whatever the mechanism by which the level is populated. If we make the reasonable assumption that the a^5F_5 level is excited by collisions with electrons, then as we shall see below, either the [O I] 6300 Å line should be detectably strong or the 3720 Å resonance line of Fe I should be very strong in absorption.

We now calculate the population of the $^1D_2$ level of O I which is the upper level of the 6300 Å line. We make the reasonable assumption that $N(\text{Fe I})/N(\text{Fe}) \leq N(\text{O I})/N(\text{O})$ and take solar abundances for Fe and O; i.e., log (Fe/O) = −1.5. In table A2 we present the parameters needed for estimating the populations of the $^1D_2$ and $^5F_5$ levels. The value of the collisional deactivation coefficient q for O I (Aller and Liller 1968) is a lower limit for electron temperature (T_e) greater than 2000° K. We are not aware of any collision strength calculations for Fe I, and the value we adopt is of the same order of magnitude as for neutral atoms such as O I and N I.

Let $\theta_e = 5040/T_e$, X be the energy of the upper level, g be the statistical weight of a level, and subscripts 2 and 1 stand for the upper and lower levels respectively. Then we find that

$$\frac{N(^1D_2)}{N(^5F_5)} = \frac{[(g_2/g_1)q_{21}\exp(-X/kT_e)]_{\text{O I}}}{[(g_2/g_1)(q_{21}/A_{21})\exp(-X/kT_e)]_{\text{Fe I}}} \cdot \frac{N(\text{O I})/N(\text{O})}{N(\text{Fe I})/N(\text{Fe})}\frac{N(\text{O})}{N(\text{Fe})} \geq 10^{-1.1\theta_e}. \quad \text{(A1)}$$

With the required aerial density (10^{14} cm^{-2}) of the $^5F_5$ level we get for the surface brightness of the 6300 Å line of O I,

$$I(6300) \geq 0.13 \times 10^{-1.1\theta_e}\ \text{ergs cm}^{-2}\ \text{s}^{-1}\ \text{sterad}^{-1}, \quad \text{(A2)}$$

which for $T_e \geq 1700°$ K results in $I(6300) \geq 6.5 \times 10^{-5}$ ergs $cm^{-2}\ s^{-1}\ sterad^{-1}$.

Spectra at 28 Å mm^{-1} (RF 1971) show no [O I] line even though the computed $I(6300)$ is well above the detection limit. It should be noted that in some emission regions in M31, the 6300 Å line has been detected, clearly separate from the nightsky line.

It is possible that T_e is lower than 1700° K in such places as shock fronts or the intercloud medium. If such conditions exist near the nucleus of M31, then for the relative populations of the excited and ground levels of Fe I we have

$$\frac{N(^5F_5)}{N(^5D_4)} \leq \frac{11}{9}\,10^{-0.86\theta_e}. \quad \text{(A3)}$$

For $T_e \leq 1700°$ K the resultant aerial density of Fe I atoms in the $^5D_4$ level is $\geq 3.2 \times 10^{17}$ cm^{-2}. This has the result that the equivalent width of the interstellar

3720 Å line of Fe I will be 2.11 Å for a turbulent velocity of 30 km s^{-1}, whereas the solar value is 1.66 Å. This may be detectable.

These numbers were obtained under the assumption that the population of Fe I levels is given by the Boltzmann formula. This is correct only for electron densities (n_e) greater than 10^6 cm^{-3}. Where do these electrons come from? If hydrogen is the main source of electrons, the measurements of RF (1971) restrict the thickness of the region to less than 10^9 cm and we do not have enough Fe. Furthermore, observations of the [O II] doublet ratio by Münch (1962) and [S II] doublet ratio (RF 1971) exclude such high electron densities. On the other hand, if the electrons are provided by carbon and other elements with lower ionization potential, one should expect N(Fe I)/N(Fe) $\ll 1$, say 10^{-2}. Under these conditions the surface density of neutral hydrogen is $\geq 3 \times 10^{23}$ cm^{-2} with the result that the mass of neutral gas required within 400 pc of the center is $\geq 10^9$ $M_\odot$, whereas the total mass in the same region is $\sim 3 \times 10^9$ $M_\odot$ (RF 1970). Furthermore, the mass of neutral hydrogen in the same region has been estimated by Burke, Turner, and Tuve (1964) to be about 10^5 $M_\odot$. These calculations lead us to believe that absorption by interstellar matter does not contribute significantly to the line at 5269 Å.

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