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NGC 4286 AND NGC 3377A: GALAXIES WITH MIXED MORPHOLOGIES BETWEEN THE DWARF Im AND dE/dSO TYPES

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ABSTRACT

Optical and radio data for the nucleated dwarf galaxy NGC 4286 show a mixed morphology between a star-forming Im type and a gas-poor dS0, N early-type dwarf. The Im dwarf NGC 3377A shows no gas depletion, but its morphology and size are similar to the "huge, very low surface brightness" (VLSB) gas-poor galaxies recently identified in the Virgo cluster. We interpret the morphology of NGC 4286 as an original Im system that has transformed itself (speciation along the dwarf sequence) into a gas-poor dS0, N by losing most (but not all) of its original gas through an internal supergalactic wind that was generated earlier by a superluminous star cluster. The remnant of this cluster has now sunk to the center by dynamical friction to form the observed unresolved bright nucleus. Such star clusters and superwinds are known to exist in many present-day starburst Sm and *amorphous* galaxies such as NGC 1569 and NGC 1705.

Subject headings: galaxies: evolution — galaxies: individual (NGC 3377A, NGC 4286) — galaxies: structure

1. INTRODUCTION

The origin of the dE early-type dwarf galaxies is still unknown, although the problem has been clarified in modern discussions (Bothun & Caldwell 1984; Binggeli 1985; Vader 1986; Binggeli & Cameron 1991, among others). Among the possibilities are (1) the transformation of giant E and S0 galaxies into dwarf remnants by the fragmentation of the giant parent by rapid and excessive mass loss by supergalactic winds early in the formation process (Mathews & Baker 1971; Larson 1974; Vigroux, Chieze, & Lazareff 1981; Dekel & Silk 1986) or by tidal action from which the resulting dwarfs are debris (Gerola, Carnevali, & Salpeter 1983); (2) the temporary quiescence of Sm and Im galaxies (Gerola, Seden, & Schulman 1980); and (3) internal transformation from original Sm or Im galaxies by mass loss due to stellar winds (Sandage 1965; Searle & Zinn 1978; Faber & Lin 1983; Wirth & Gallagher 1983).

Proposition 2 is now ruled out by the observation that the H I content of dE galaxies is generally undetected to a significantly low flux level (Bothun et al. 1985; Hoffman et al. 1985, 1987). The two chief objections to proposition 3 have been (*a*) many dE galaxies have globular cluster-like nuclei that reach absolute magnitude $M_B = -11$, whereas most (present day) Im galaxies do not, and (*b*) the flattening distribution of complete samples of dE and Im galaxies differ. However, the flattening problem may not exist when the data are properly binned (Ichikawa, Wakamatsu, & Sandage 1986; Ferguson & Sandage 1989) or when more precise data are used (Binggeli & Cameron 1991). The nucleus problem is addressed as part of this *Letter*.

In a test of proposition 3 we have looked for "missing link" galaxies with the mixed morphology of an underlying dE or dS0 but with evidence of current star formation distributed globally rather than only in the center as in NGC 185 and NGC 205 (Baade 1951; Johnson & Gottesman 1983). We report in this *Letter* observations of two dwarf galaxies that have the global mixed morphology of what we expect for "missing link" forms in various transformation stages.

2. NGC 4286

2.1. *Optical Morphology*

The early-type dwarf NGC 4286 forms an apparent triplet with the giant NGC 4278 (E1) and NGC 4283 (E0) with an angular separation from NGC 4278 of 8'.7. But NGC 4283 may be in the background as judged by its large redshift of $v_0 =$ 1053 km s^{-1}. The v_0 redshifts of NGC 4278 and NGC 4286 are 594 km s^{-1} and 638 km s^{-1}, respectively. At the adopted distance of 10 Mpc for the pair (see the next paragraph), the projected linear separation of NGC 4286 from NGC 4278 is small at 23 kpc. Figure 1 (Plate L2) shows the geometrical configuration of the three galaxies. The print is from a yellow sensitive plate taken with the Palomar Hale 200 inch reflector.

The estimated distance modulus of NGC 4278 is $(m-M) = 30$ based on the brightest apparent magnitude (about $V = 21$) of its globular clusters. At this distance, the absolute magnitude of the nucleus with $B = 17$ is $M_B = -13$, similar to the brightest nuclei in dE dwarfs in the Virgo cluster (Binggeli & Cameron 1991).

The optical image of NGC 4286 is not quite normal for a protypical dE or dS0 galaxy but is mixed between Sm/Im and dS0. There is a hint of structure over the disk in the yellow image (Fig. 2*a* [Pl. L3]) rather than the smooth profile of classical dE/dS0 dwarfs (Sandage & Binggeli 1984). This structure becomes conspicuous in the blue image where knots (stars or H II regions) exist over the face and where a weak "spiral pattern" exists in the outer envelope (Fig. 2*b* [Pl. L3]).

The surface brightness of NGC 4286 is consistent with either classification. Combining the Zwicky apparent magnitude of $B_T = 14.7$ with the effective semimajor and semiminor axes of

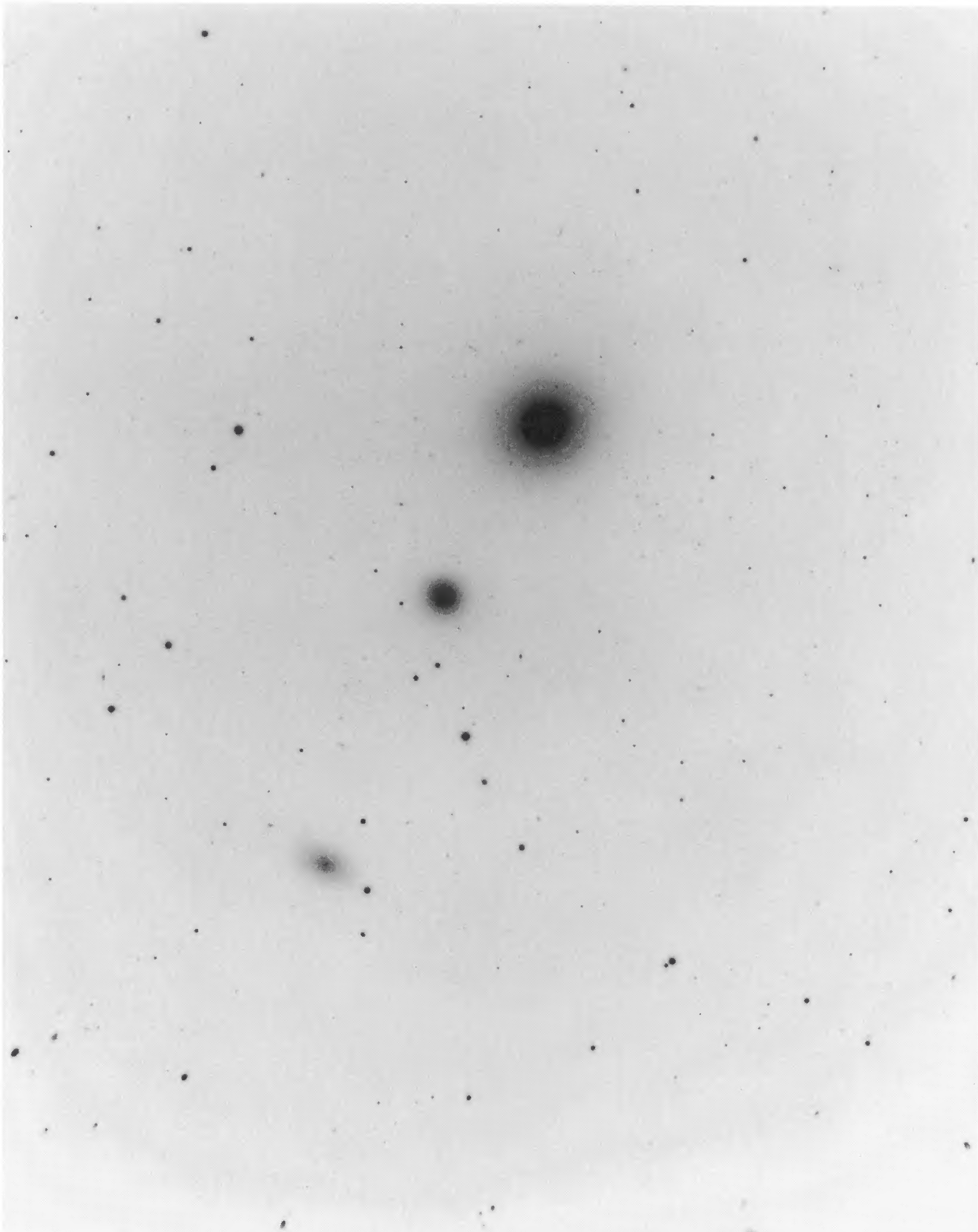

FIG. 1.—Wide angle view of the apparent triplet of NGC 4278 (E1), NGC 4283 (E0), and NGC 4286 (dS0, N pec). NGC 4278 and NGC 4286 form a kinematic pair. NGC 4283 (the middle galaxy) may be in the background based on its larger redshift and lack of resolution into globular clusters. The reproduction is from a yellow (103aD + GG11) plate taken on 1954 February 7/8 with the Palomar Hale 200 inch telescope.

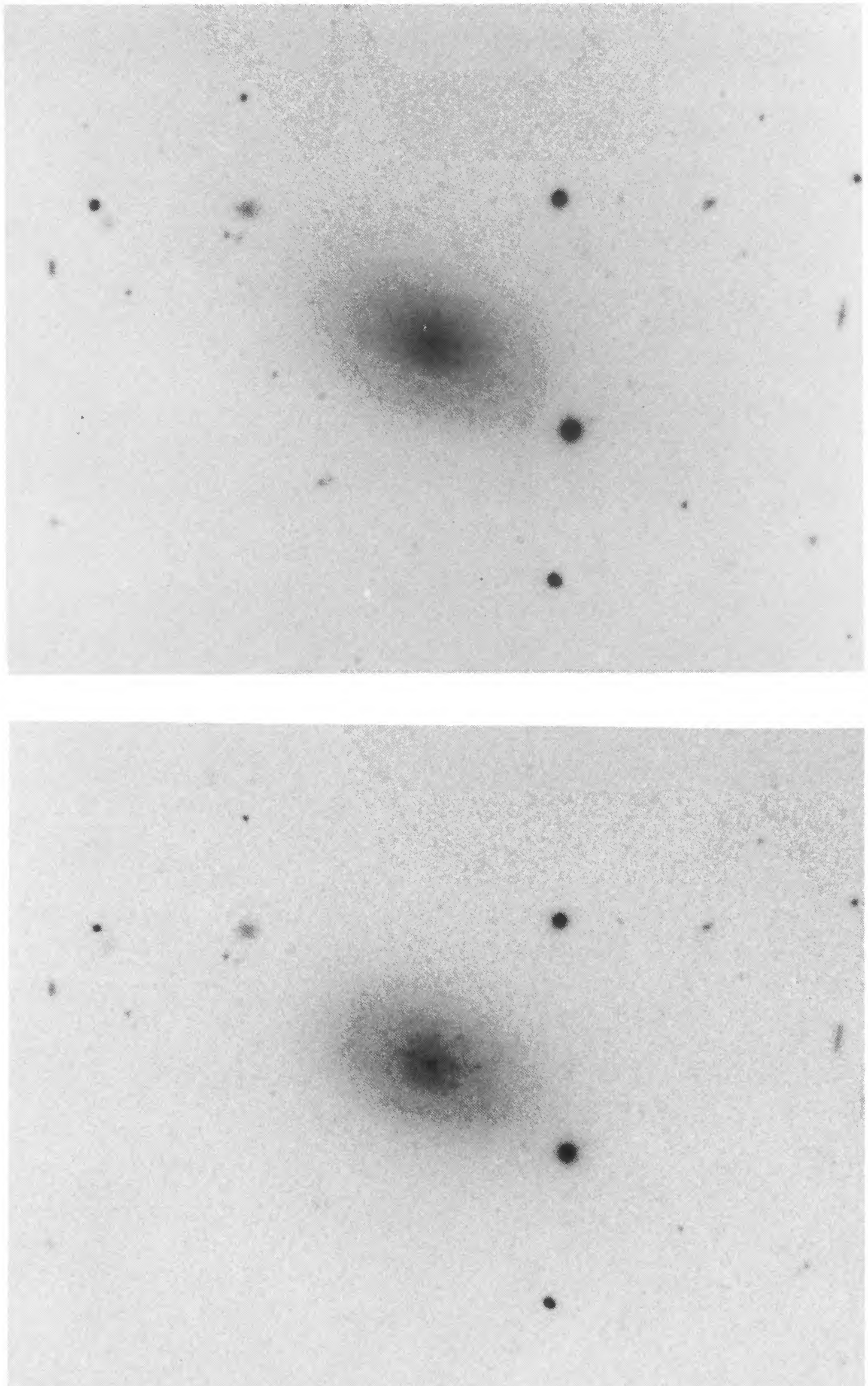

FIG. 2*b*

FIG. 2.—(*a*) Image of NGC 4286 from the same yellow plate used in Fig. 1. (*b*) Image of NGC 4286 from a blue (103a0 with no filter) Palomar plate taken by H. C. Arp on 1968 April 27/28.

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30″ and 20″ gives an average surface brightness inside the effective area of 23.7 B mag/(arcsec)^2. The absolute magnitude of the galaxy is $M_{B(T)} = -15.3$. These fit the calibration of the $\langle SB \rangle - M$ relation for dE and dS0 galaxies in the Virgo cluster and other aggregates (Binggeli, Sandage, & Tarenghi 1984; Sandage & Perelmuter 1990, Fig. 11). The data are also consistent with that same relation for Im dwarfs (Binggeli 1985; Binggeli & Cameron 1991).

2.2. *The* H I *Content of NGC 4286*

Because of the mixed morphology we began an investigation of the H I content of NGC 4286. We made a positive detection of H I with the Arecibo 305 m telescope[1] using the dual circular feed in 1988 January and June. A subsequent detection was made by Lees, Van Gorkom, & Knapp (1989). We obtained a 2 km s^{-1} resolution spectrum corrected for instrumental effects in the standard way (Helou, Hoffman, & Salpeter 1983). This spectrum, Figure 3, shows a double-peaked profile with $\int S\,dV = 579$ mJy km s^{-1} (669 mJy km s^{-1} after correction for the 3.′2 beam size) centered on the heliocentric velocity of $v_{\odot} = 644$ km s^{-1}, with a 50% profile width of $\Delta V = 113$ km s^{-1}.

Major-axis mapping at lower sensitivity allows us to say only that the NNW side of the galaxy is receding from the observer. This is the sense that a rotation is expected to have if the "spiral arm" seen in Figure 2*b* is trailing, known to be characteristic of all spirals.

3. NGC 3377A = UGC 5889

3.1. *Optical Morphology*

NGC 3377A is a dwarf companion of the nearby prototype E6 galaxy NGC 3377 at an angular separation of 7′. The distance of NGC 3377, with a redshift of $v_0 = 591$ km s^{-1}, is judged to be ~10 Mpc, based, as for NGC 4278 as well, on the easy detection of globular clusters in its envelope beginning at about $V = 21$. The redshift of $v_0 = 446$ km s^{-1} for NGC 3377A, measured by Lewis (1987), shows that the dwarf is a companion of NGC 3377 at the small projected linear separation of 20 kpc.

Figure 4 (Plate L4) shows the optical image of NGC 3377A made from an original blue (103a0 + GG1) 200 inch plate. The principal characteristics are (*a*) a very low surface brightness and (*b*) the large angular diameter of $D_{25} = 2.'0$ (from the RC2).

[1] The Arecibo Observatory is part of the National Astronomy and Ionosphere Center operated by Cornell University under contract with the National Science Foundation.

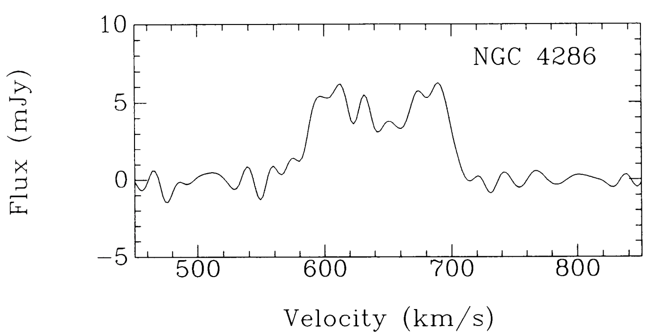

FIG. 3.—The observed H I profile of NGC 4286 obtained with the Arecibo 305 m radio telescope.

The large linear diameter of 5.8 kpc, the Zwicky (total) magnitude of $B_T = 15.0$, and the mean surface brightness averaged over the D_{25} diameter of 23.9B mag/(arcsec)^2 make the galaxy similar to the bright end of the "huge very low surface brightness systems" (VLSB) in the Virgo cluster (Binggeli, Sandage, & Tammann 1985, hereafter BST).

Many knots (stars or H II regions) exist over the face of NGC 3377A, similar to the VLSB prototype Virgo galaxies IC 3475 (Reaves 1956) and IC 3418 in BST (Table XIV). The bright knot near the center of the image may be an eventual central nucleus that will sink to the center by dynamical friction (Norman 1985). Its abolute magnitude is $M_B = -11$, based on its estimated blue magnitude of $B = 19$.

The 21 cm H I flux measured by Lewis (1987) with the Arecibo 305 m telescope is $\int S\,dV = 3834$ mJy km s^{-1}, corrected for beam filling. The profile is single peaked (the galaxy is close to face-on) with a 50% profile width of 45 km s^{-1}.

4. DISCUSSION

4.1. *Radio Data*

The hydrogen mass-to-blue luminosity ratio $M_H/L = 1.34 \times 10^{-10} \times 10^{0.4B(T)} \int S\,dV$ is 0.068 (solar units) for NGC 4286 and 0.52 for NGC 3377A. Even if we "correct" NGC 3377A's Zwicky magnitude to 14.2, following Lewis (1987), the resulting $M_H/L = 0.23$ is still very large. We show below that the hydrogen surface density for NGC 3377A is *typical of Sc galaxies rather than S0s*.

The M_H/L value for NGC 4286 is also high even for S0 galaxies. The NGC 4286 value lies near the *upper end* of the S0 distribution summarized by Haynes et al. (1990, hereafter HHBB) for galaxies in the Local Supercluster. The M_H/L ratio for NGC 4286 is nearer *the median of the Sa distribution* (Roberts 1969) than that of S0s, showing H I richness of this dwarf.

The H I mass $M_H = 236 \times (d/\text{Mpc})^2 \int S\,dV$ is $1.6 \times 10^7\ M_{\odot}$ for NGC 4286 and $9.0 \times 10^7\ M_{\odot}$ for NGC 3377A. Using the optical D_{25} diameters listed in the RC2 and the distance of 10 Mpc gives mean H I surface densities of 6.6×10^5 and 3.4×10^6 solar masses of H I per square kpc for NGC 4286 and NGC 3377A, respectively. This hydrogen surface density for NGC 3377A is much higher than the mean values for either S0, Sa, or Sb galaxies, but is similar to the mean value for Sc galaxies (HHBB, Fig. 1).

Our conclusion, based on the abnormal H I content for their underlying dE/dS0 dwarf morpologies, is that these two galaxies are candidates for the sought after "missing links."

4.2. *Stellar Winds as the Gas Removal Mechanism*

The value of $M_H/L = 0.07$ for NGC 4286 is nearly an order of magnitude smaller than that for the Sm and Im dwarfs in the Virgo cluster (Hoffman et al. 1985, 1987). If NGC 4286 was once a late-type dwarf of type Sm or Im, then most of the gas must have been removed, and an intense nucleus of absolute magnitude $M_B = -13$ has formed.

The connection between the two events seems inevitable. Present-day starburst galaxies identify the mechanism to be momentum transfer to the internal gas by supernovae and robust star-driven winds. M82 was the first galaxy of this kind in which an "explosive" outward wind was observed (Lynds & Sandage 1963; Burbidge et al. 1964) with recent confirmation of starburst winds by Chevalier & Clegg (1985), McCarthy,

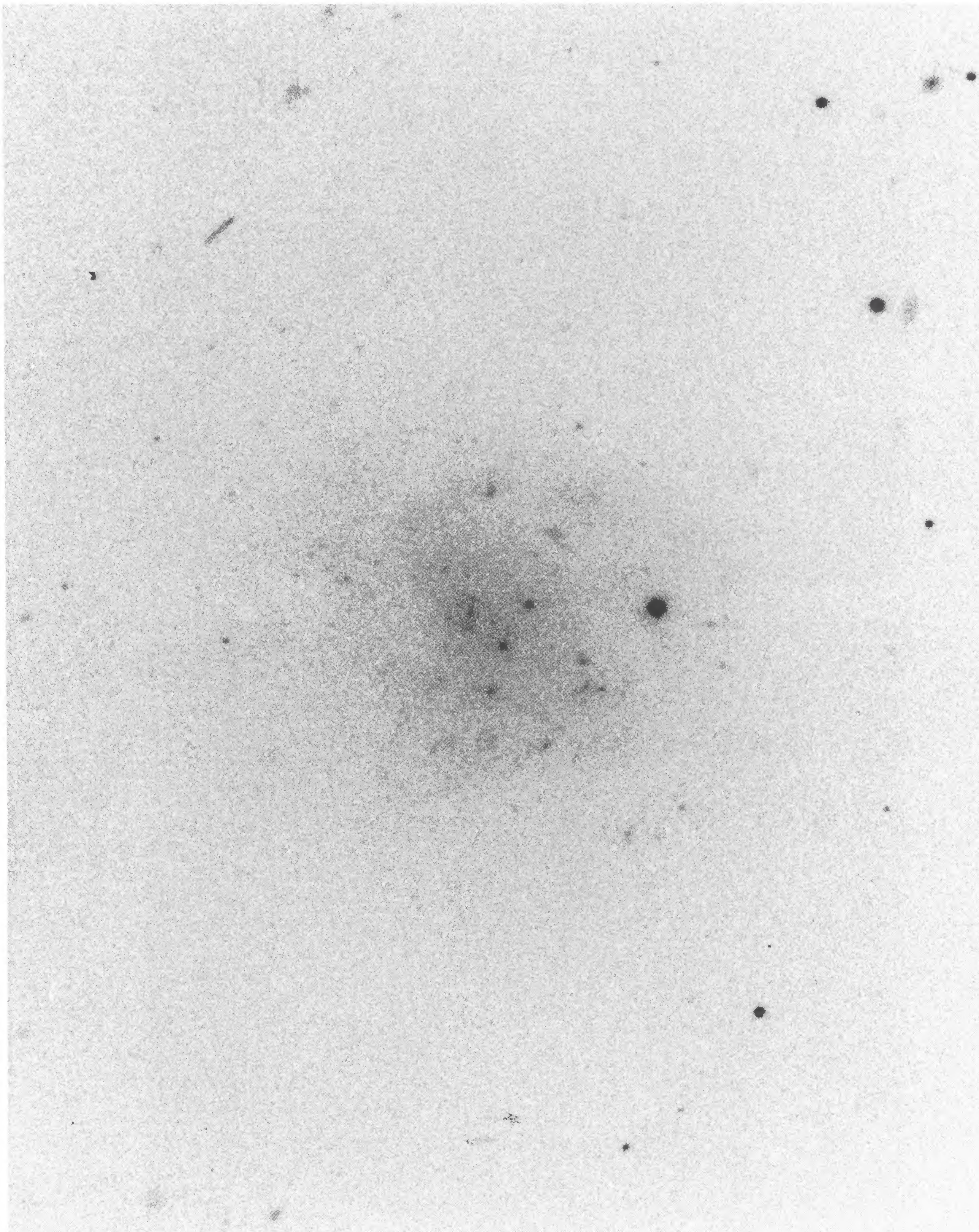

FIG. 4.—Image of NGC 3377A from a blue plate (Eastman 103a0 + GG1) taken by Baade with the Palomar 200 inch telescope on 1953 January 19/20

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Heckman, & Van Breugel (1987), Heckman, Armus, & Miley (1987) among others.

Similar large-scale galactic winds are known in NGC 1569 (Arp & Sandage 1985) and NGC 1705 (Meurer, Freeman, & Dopita 1989; Meurer 1991). Super star clusters of absolute magnitude $M_B = -14$ also exist in both these galaxies. Meurer et al. (1989) and Meurer (1991) calculate that all the gas will be driven out of NGC 1705 by the galactic winds on a time scale of less than 10^8 yr and that the supercluster will sink to the center by dynamical friction in as short a time scale as 5×10^7 yr (Norman 1985) forming the nucleus of a dE or dS0 dwarf (see Binggeli 1985 for fading vectors in surface brightness space, consistent with this picture).

Super star clusters and galactic winds exist in most other amorphous galaxies as classified for the RSA (Sandage & Brucato 1979). These include NGC 625, 1140, 1569, 1705, 1800, 3125, 3353, 3773, and 5253. Supergalactic winds are also known to exist in all starburst galaxies (de Young 1978, 1981, 1986; Ostriker & McKee 1988; Heckman et al. 1990), due either to the energy input of supernovae or of the OB stars of the superclusters.

Dwarf galaxies are the most prone to self-transformation (Sandage 1965) from late to early-type types because the escape velocity of the gas from them is small. Such mass loss as a function of escape velocity is also widely recognized as the only reasonable way to understand the correlation between metallicity and absolute magnitude for dE galaxies over a range of 7 absolute magnitudes.

It is our proposition that NGC 4286 is a galaxy in transition from Im to dS0. It is also our proposition that NGC 3377A has not yet been transformed but that it is similar to IC 3475 in the Virgo Cluster from which the gas has been swept (Vigroux et al. 1986), and which is the prototype of the "huge low surface brightness" early-type galaxies that have been identified in that cluster (Sandage & Binggeli 1984).

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