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STAR FORMATION IN THE TIDAL TAIL OF THE LEO TRIPLET GALAXY NGC 3628

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ABSTRACT

Deep CCD images of the Leo Triplet in the B and I bands were obtained with the Burrell-Schmidt telescope at Kitt Peak National Observatory to study the $\sim$80 kpc stellar tail, or "plume," extending from NGC 3628, which resulted from the tidal effects of its companion galaxies NGC 3627 and NGC 3623. This plume consists of clumpy star formation regions that are near previously measured high-resolution H I peaks. Comparison of our $B-I$ colors and B luminosities with star cluster evolution models indicates star-forming ages of a few times 10^8 years and complex masses of 10^6 $M_\odot$, corresponding to a star formation efficiency of 3% overall in the plume, or about 26% at the H I peaks.

Key words: galaxies: individual (NGC 3628) — galaxies: interactions — galaxies: stellar content

1. INTRODUCTION

The Leo Triplet, comprising the galaxies NGC 3623, NGC 3627, and NGC 3628, has been the subject of much study since its original discovery by Zwicky (1956). Zwicky reported an optical plume extending from NGC 3628, which is visible in an uncalibrated photographic image by Kormendy & Bahcall (1974). The plume extends for 40′ east of NGC 3628, or $\sim$80 kpc at an assumed distance of 6.7 Mpc to the Leo Triplet (de Vaucouleurs 1975). Burkhead & Hutter (1981) made photoelectric drift scans and a deep R-band photograph of the system to measure the total brightness and color. Hughes, Appleton, & Schombert (1991) obtained a deep IIIa-J photograph, as well as short B- and V-band CCD images, of the plume to measure its color; they also discovered 100 μm emission in the plume caused by its dilute radiation field. Haynes, Giovanelli, & Roberts (1979) measured the plume to have an unusually narrow H I velocity width of 17 km s^{-1}. They reproduced the Kormendy & Bahcall image with high contrast to enhance plume details.

Rots (1978) and Haynes et al. estimated a total H I mass in the plume of 5.4×10^8 $M_\odot$, which is approximately 15% of the total H I mass observed in the main body of NGC 3628. Zhang, Wright, & Alexander (1993) observed CO and H I in NGC 3627 at high resolution and speculate from the large molecular-to-atomic ratio and underabundant H I mass that some H I may have been converted into H_2, or that NGC 3627 may have lost some of its outer H I to NGC 3628 during the tidal encounter. Millimeter observations of the CO $J = 1$–0 emission from the Triplet made by Young, Tacconi, & Scoville (1983) at 50″ resolution show no CO in the plume of NGC 3628. In the central regions of NGC 3627 and NGC 3628, the ratio of blue luminosity to CO luminosity is normal for their Hubble types, indicating that the star formation efficiency has not been altered by the close encounter. However, *ROSAT* observations (Dahlem et al. 1996) and radio continuum observations (Condon et al. 1982; Carral, Turner, & Ho 1990) show that NGC 3628 is a circumnuclear starburst galaxy with a hot gas outflow. H I and OH observations of NGC 3628 reveal high densities and a possible expanding spiral arm in the central regions (Schmelz, Baan, & Haschick 1987a, 1987b).

Rots (1978) constructed restricted three-body orbital models for the tidal interactions between NGC 3628 and its companion NGC 3627, which reproduce the formation of a long plume and give a time of 8×10^8 yr since perigalacticon. Higher resolution calculations by Boissé, Casoli, & Combes (1987) concur with this timescale. Their models and CO observations, as well as the observations of Zhang et al. (1993), support the idea of infalling gas leading to intense star formation in the central regions of these galaxies. They also generate a long eastern tidal plume in NGC 3628, with material from the outer parts of that galaxy. (The simulation does not consider the possibility of mass transfer from NGC 3627.) The perigalacticon distance is estimated to be 25 kpc. In this paper, we present deep CCD images in the B and I bands to measure colors and luminosities of star clumps in the tidal plume of NGC 3628, from which we infer their ages and masses.

2. OBSERVATIONS, DATA REDUCTION, AND ANALYSIS

We obtained deep-exposure CCD images of the Leo Triplet in both the B and I bands at Kitt Peak National Observatory using the 0.6 m Burrell Schmidt telescope in 1995 April and in 1997 February. The scale of the images is 2″.03 pixel^{-1}, with a field of view of 58′. There were 26 B-band images totaling 26,000 s and 20 I-band images totaling 19,800 s, which were reduced and combined following standard procedures using IRAF. A summary of the observations is in Table 1. Sky flats were averaged over the entire run. The images were mosaicked in order to produce a total field of view of 1°.16 × 1°.71. The B-band mosaic is shown in Figures 1 and 2; Figure 1 is reproduced on a logarithmic scale, with saturated galaxies in order to highlight faint outer features, while Figure 2 has a contrast selected to optimize the galaxies. NGC 3628 is the edge-on galaxy in the north; NGC 3627 is south of it, while NGC 3623 is to the southwest. A saturated star between NGC 3628 and NGC 3623 appears as a large fuzzy object.

An enlargement of the tidal plume of NGC 3628 is shown in Figure 3. Four star-forming clumps are labeled, with approximate boundaries marked by rectangles. A faint structure also extends to the northeast from NGC 3627. Based on a comparison of this image with the Palomar

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TABLE 1

OBSERVATIONS

Date	Number of *B*-Band Images	Exposure Time (s)	Number of *I*-Band Images	Exposure Time (s)
1995:				
Mar 31	3	1000	2	1000
Apr 1	6	1000	...	...
Apr 2	...	...	3	1000
Apr 4	12	1000	...	...
1997:				
Feb 6	4	1000	5	3 × 1000, 2 × 900
Feb 8	...	...	6	1000
Feb 9	1	1000	4	1000
Total......	26	26000	20	19800

Observatory Sky Survey, we believe that this feature is an artifact caused by a bright star off-image or from an uneven sky. The feature does not coincide with the H I contours shown in Figure 1, nor is it present in the *I*-band image.

Standard stars (Landolt 1983) observed during the run were used to calibrate the images, and a Milky Way extinction of 0.19 mag in *B* (de Vaucouleurs et al. 1991) was applied. Hughes et al. (1991) argue that there is very little dust in the plume, so we have made no galaxy extinction corrections.

Radial profiles of both the disk and the plume of NGC 3628 are shown in Figures 4*a* and 4*b*, respectively. The cuts were made directly across the center of the galaxy from edge to edge, and from the eastern tip of the plume to the western tip. The disk profile is approximately exponential, as expected for spiral galaxies (Freeman 1970). However, there is a sharp cutoff at the edges near $\pm 7'$, which we interpret to be the result of tidal shearing. This truncation was also observed in the *R* band by Burkhead & Hutter (1981) and is reproduced by the models of Rots (1978). The light profile of the plume is approximately constant, 26.5 mag arcsec^{-2}, which is the same surface brightness as the optical edges of the disk. These observations support the theory that the tail was formed from material in the outer galaxy (Rots 1978; Haynes et al. 1979). The bright clumps labeled in Figure 3 are evident in the plume profile.

A $B-I$ color map was made from the calibrated images. The $B-I$ radial profile of the plume is shown in Figure 5. It is noisy in the east because of the faintness of the *B* image. The color is essentially constant along the length of the plume and is the same as in the outer regions of the galaxy, $B-I = 1.6 \pm 0.3$. This similarity of the plume and disk colors is in agreement with the $B-V$ measurements by Burkhead & Hutter (1981) and Hughes et al. (1991).

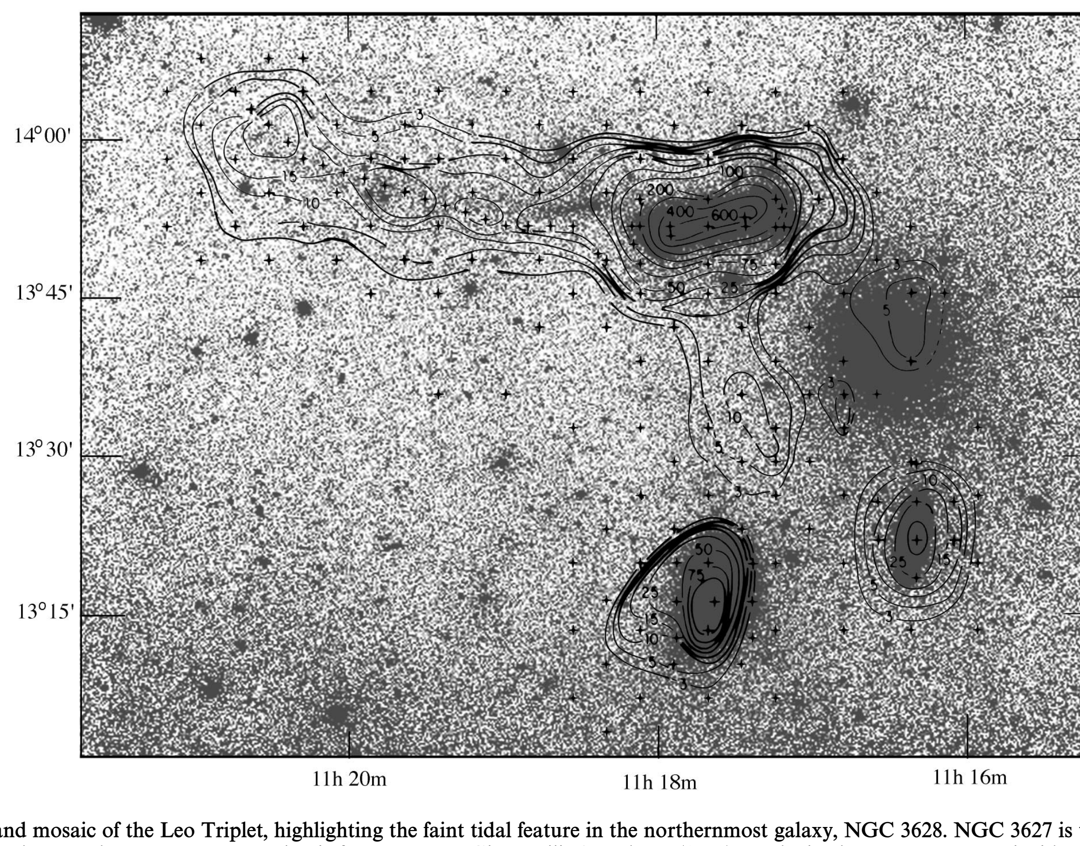

FIG. 1.—*B*-band mosaic of the Leo Triplet, highlighting the faint tidal feature in the northernmost galaxy, NGC 3628. NGC 3627 is to the south; NGC 3623 is to the southwest. The H I contour overlay is from Haynes, Giovanelli, & Roberts (1979). Peaks in the H I contours coincide approximately with optical clumps.

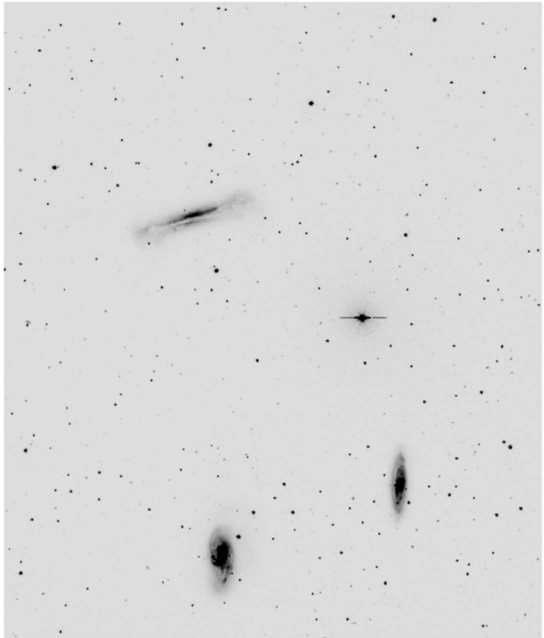

FIG. 2.—*B*-band image of the Leo Triplet, highlighting the individual galaxies.

In order to estimate the ages and masses of the individual clumps labeled 1 through 4 on Figure 3, we subtracted the underlying average tail intensity from the *B* and *I* intensities to derive $B-I$ colors for the clumps alone. The underlying tail intensities as a function of radius are shown in Figures 6*a* and 6*b* for the *B* and *I* bands, respectively. The clump $B-I$ peaks range from 0.9 to 2.4. Within our measurement errors, these colors are consistent with the $B-V$ colors of Hughes et al. (1991) except for our clump 4, which is considerably redder than their corresponding feature A. From a comparison of our clump colors with an interpolation of the star cluster evolution models of Leitherer & Heckman (1995) and Worthey (1994) for a burst of star formation, a Salpeter initial mass function, and solar metallicity, we estimate that the peaks have ages of a few times 10^8 yr, as listed in Table 2. If the plume material does originate from the outer disk of NGC 3628, then its metallicity may be less than solar. Lower limits to the ages and masses, corresponding to models for a metallicity of 0.25 $Z_\odot$, are also listed in Table 2. The age of clump 4 is particularly uncertain because its *B* luminosity is so faint. These ages are approximately the same as the time since perigalacticon, which supports the inference by Young et al. (1983) that large-scale star formation occurred also in the main galaxy disk then.

The *B* magnitudes were converted to *V* magnitudes using an interpolation of the Leitherer & Heckman and Worthey models to determine $B-V$ for our ages. From these magnitudes, we inferred the stellar clump masses based on the relation between *V* magnitude and cluster masses of different ages established in the LMC by Girardi et al. (1995). Our cluster luminosities and ages were off the Girardi et al. scale, so we extrapolated their curves to higher masses. We assumed that the 10^6 and 10^7 $M_\odot$ curves were parallel to the curves for 10^4 and 10^5 $M_\odot$ and equally spaced. The results for individual clumps are listed in Table 2; the average clump mass was about 10^6 $M_\odot$. These masses are reasonable for star-forming complexes (see, e.g., Efremov 1995). The total mass in all the clumps equals 2.0×10^7 $M_\odot$ (or 1.2×10^7 $M_\odot$ for 0.25 $Z_\odot$).

For comparison, we note that the "Superantennae" pair of closely interacting galaxies studied by Mirabel, Lutz, &

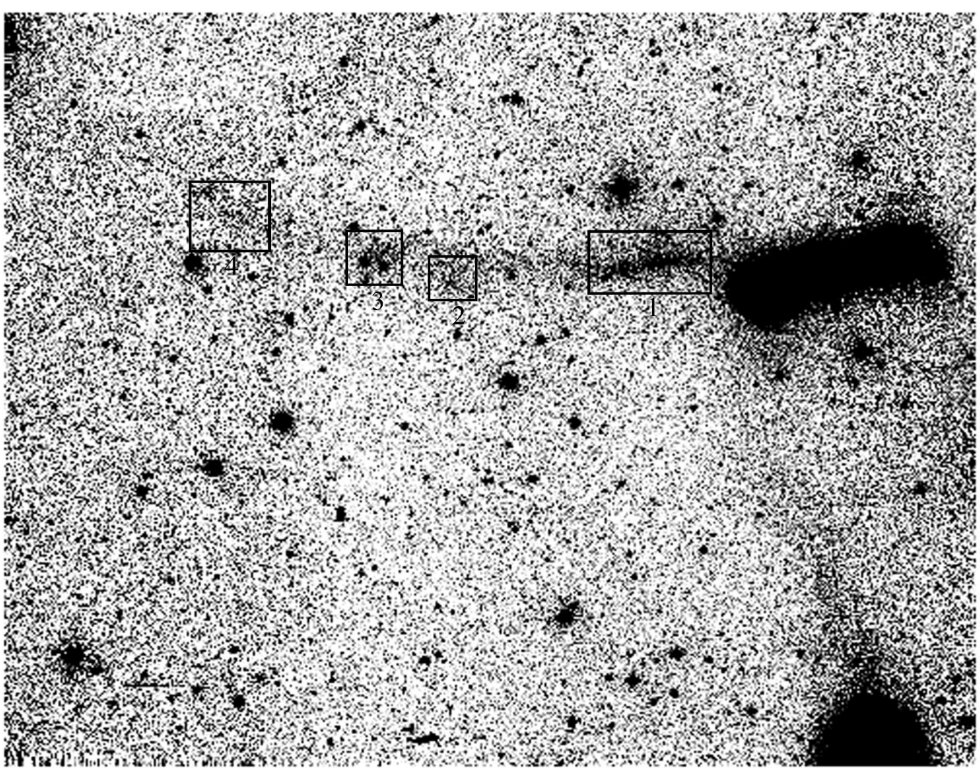

FIG. 3.—*B*-band image of NGC 3628 showing the tidal plume, with NGC 3627 to the south

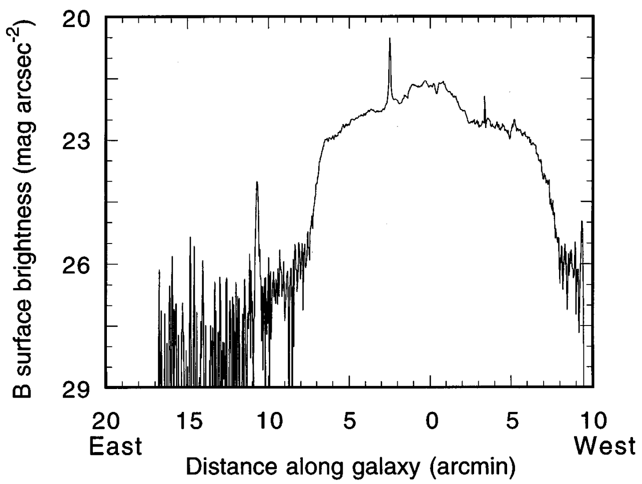

FIG. 4*a*

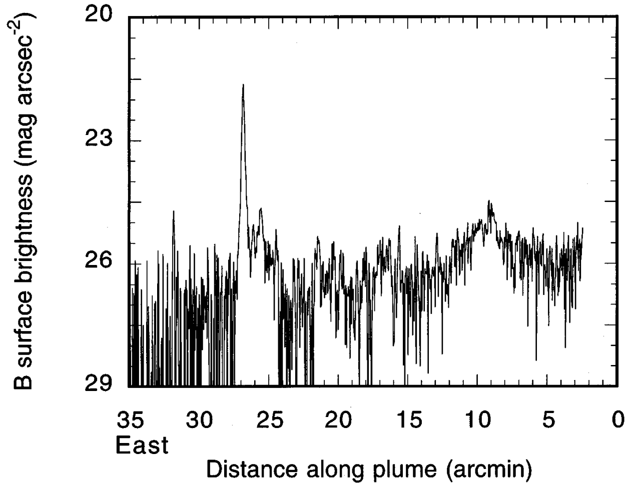

FIG. 4*b*

FIG. 4.—(*a*) Radial profile through the main disk of NGC 3628; the center is at 0′. Note the truncated edge of the disk at $\pm 7'$. (*b*) Radial profile of the plume, from the eastern tip on the left to the galaxy center on the right.

Maza (1991) have long narrow tails like the Leo plume, extending nearly 200 kpc each. There are nine condensations in the two tails, with $B-V$ colors ranging from 0.4 to 1.0; these colors are similar to the $B-V$ colors of the Leo plume clumps, 0.9 (Burkhead & Hutter 1981) and 0.5–0.7 (Hughes et al. 1991), with $B-R$ colors ranging from 1.0 to 1.6. Mirabel et al. infer from the colors that the Superantennae clumps are composed of the same stellar mix as the outer disk, with the exception of a particularly blue clump that is located at the tip of one of the tidal tails. The luminosity of this star-forming clump is equivalent to a mass of several times $10^8\ M_{\odot}$.

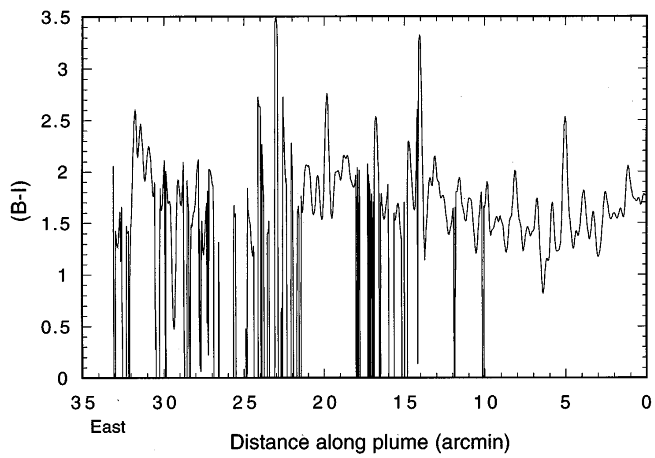

FIG. 5.—Radial profile along the plume from a $B-I$ color map, showing the nearly constant plume color.

3. COMPARISON OF OPTICAL AND RADIO DATA

Our final *B* image was compared with the H I contours by Haynes et al. (1979); an overlay is shown in Figure 1. The plume is the narrowest neutral hydrogen emission profile observed outside our Galaxy. The optical plume correlates well with the H I contours in both its length and clumpiness; the stellar luminosity peaks are approximately coincident with the H I peaks. The plume's total stellar mass relative to the total hydrogen mass is comparable to the star-to-gas ratio for the main disk (Burkhead & Hutter 1981).

We divided the plume into four major gas clumps based on the peaks in the H I surface density contours, as indicated also in Haynes et al. (1979). The approximate central

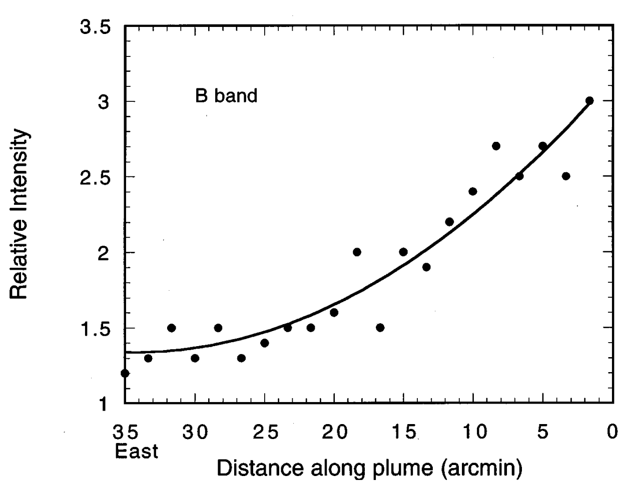

FIG. 6*a*

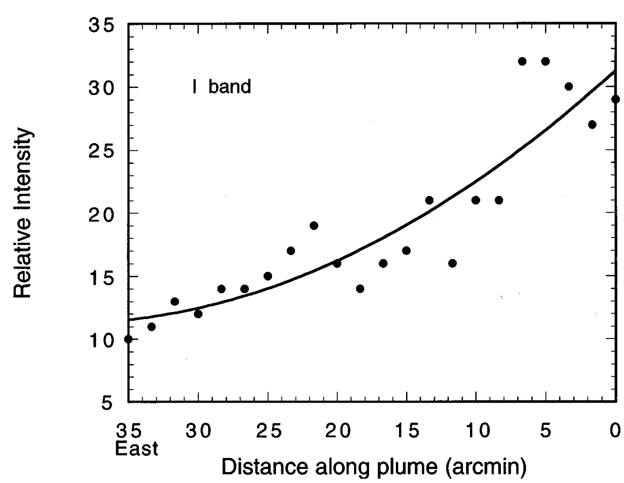

FIG. 6*b*

FIG. 6.—Relative intensity of the average plume in the (*a*) *B* band and (*b*) *I* band

TABLE 2

PHOTOMETRY OF STELLAR CLUMPS IN THE PLUME

Clump	Relative Intensity: Clump B	Clump I	Off-Clump B	Off-Clump I	$B-I$	Age (10^8 yr) 1 $Z_\odot$	0.25 $Z_\odot$	Mass (10^6 $M_\odot$) 1 $Z_\odot$	0.25 $Z_\odot$
1 (peak)	8.5	77	2.7	30	1.51 ± 0.15	7.6	4.8	2 ± 0.2	1.5
1 (average)	5.5	55	2.7	30	1.62 ± 0.30	7.7	4.9	9 ± 0.3	6
2	3.3	8	1.7	1	0.84 ± 0.22	0.12	0.08	0.2 ± 0.1	0.1
3	4	29	1.6	15	1.15 ± 0.50	1.8	0.39	4 ± 0.5	1
4	1.8	19	1.4	12	2.35 ± 0.50	160	40	7 ± 0.5	5

TABLE 3

H I MASSES OF CLUMPS IN THE PLUME

Clump	Approximate α (B1950.0)	Approximate δ (B1950.0)	Average Radius (kpc)	Mass (10^7 $M_\odot$)
1	11 18 45	13 50 00	2.7	0.75
2	11 19 15	13 51 00	3.3	1.1
3	11 19 45	13 52 00	5.3	3.0
4	11 20 30	14 00 00	5.1	2.7
Total				7.6

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

coordinates of these H I peaks are listed in Table 3. We have included in Table 3 the average linear radius of each clump, typically 4–6 kpc. Note that the 3'.3 beamwidth used for these H I observations corresponds to 6.4 kpc, so that the clumps are not resolved. This constraint means that our clump masses are only approximate. We estimated the surface area of our clumps by measuring the major and minor axes of the H I peak contours of 20 K km s^{-1}. The boundaries of these peaks are similar to those of the stellar clumps. We subtracted the plume's underlying H I emission of 5 K km s^{-1} from these values. Based on the Haynes et al. (1979) conversions, we determine lower limits for the masses of the clumps to be (0.75–3) $\times$ 10^7 $M_\odot$, as listed in Table 3.

The star formation efficiency of the plume was estimated to be 2%–4% based on summing the stellar clump masses [(1–2) $\times$ 10^7 $M_\odot$] and dividing by the total H I mass in the plume (5.4 $\times$ 10^8 $M_\odot$). If we consider the masses of the stellar clumps relative to the masses of only the H I clumps (7.6 $\times$ 10^7 $M_\odot$), the efficiency is 13%–26%. These efficiencies are consistent with normal star formation efficiencies in giant molecular clouds in our Galaxy observed on large and small scales (e.g., Lada, Strom, & Myers 1993; Elmegreen 1992).

4. CONCLUSIONS

We have obtained deep optical CCD images of the 80 kpc plume of NGC 3628. The exponential disk of the galaxy appears to be tidally truncated. The color is nearly constant along the plume and is the same as in the outer envelope of NGC 3628, as expected for a tidal origin. Optical clumps in the plume are nearly coincident with H I peaks. The derived clump ages of several times 10^8 yr are consistent with star formation ensuing at the time of perigalacticon. Their stellar masses of a few times 10^6 $M_\odot$ are typical of massive star-forming complexes. Their total stellar mass compared with the H I mass suggests a star formation efficiency in the plume of about 4% overall, or approximately 26% in the regions of the star formation.

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