INFRARED NARROWBAND TOMOGRAPHY OF THE LOCAL STARBURST NGC 1569 WITH THE LARGE BINOCULAR TELESCOPE/LUCIFER

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ABSTRACT

We used the near-IR imager/spectrograph LUCIFER mounted on the Large Binocular Telescope to image, with subarcsecond seeing, the local dwarf starburst NGC 1569 in the JHK bands and He i 1.08 μm, [Fe ii] 1.64 μm, and Brγ narrowband filters. We obtained high-quality spatial maps of He i 1.08 μm, [Fe ii] 1.64 μm, and Brγ emission across the galaxy, and used them together with Hubble Space Telescope/Advanced Camera for Surveys images of NGC 1569 in the Hα filter to derive the two-dimensional spatial map of the dust extinction and surface star formation rate (SFR) density. We show that dust extinction (as derived from the Hα/Brγ flux ratio) is rather patchy and, on average, higher in the northwest (NW) portion of the galaxy (Eγ(B − V) < 0.71 mag) than in the southeast (Eγ(B − V) < 0.57 mag). Similarly, the surface density of SFR (computed from either the dereddened Hα or dereddened Brγ image) peaks in the NW region of NGC 1569, reaching a value of about 4 × 10−3 M⊙ yr−1 pc−2. The total SFR as estimated from the integrated, dereddened Hα (or, alternatively, Brγ) luminosity is about 0.4 M⊙ yr−1, and the total supernova rate from the integrated, dereddened [Fe ii] 1.64 μm luminosity is about 0.005 yr−1 (assuming a distance of 3.36 Mpc). The azimuthally averaged [Fe ii] 1.64 μm/Brγ flux ratio is larger at the edges of the central, gas-deficient cavities (encompassing the superstar clusters A and B) and in the galaxy outskirts. If we interpret this line ratio as the ratio between the average past star formation (as traced by supernovae) and ongoing activity (represented by OB stars able to ionize the interstellar medium), it would then indicate that star formation has been quenched within the central cavities and lately triggered in a ring around them. The number of ionizing hydrogen and helium photons as computed from the integrated, dereddened Hα and He i 1.08 μm luminosities suggests that the latest burst of star formation occurred about 4 Myr ago and produced new stars with a total mass of ∼1.8 × 106 M⊙.

Key words: galaxies: dwarf – galaxies: individual (NGC 1569) – galaxies: irregular – galaxies: starburst – galaxies: star formation

1. INTRODUCTION

Understanding the star formation activity and history of local dwarf galaxies is of high astrophysical relevance. In fact, they represent ideal laboratories for studying how star formation occurs in low-metallicity environments that, at the same time, do not show any global, ordered kinematic structure as in disk galaxies. As such, dwarf galaxies allow us to study how stellar feedback alone affects the physics, kinematics, and chemical enrichment of the interstellar medium (ISM). Nearby, star-forming dwarf galaxies that are metal-poor and gas-rich are often compared to the first galaxies in the early universe (see Izotov & Thuan 1999), which were the first structures to collapse from primordial density fluctuations and gave rise to larger systems through mergers (White & Frenk 1991; Kauffmann et al. 1993; Cole et al. 1994). They are also referred to as the possible local counterparts of starbursting galaxies that, at moderate redshift, dominate the faint galaxy counts at blue wavelengths (Broadhurst et al. 1992; Lilly et al. 1995).

The nearby galaxy NGC 1569 is considered to be the archetype starburst dwarf galaxy for several reasons. First of all, it is gas-rich and relatively metal-poor: at the revised distance of 3.36 Mpc (Grocholski et al. 2008; so that M⊙ ≃ 18), its H i and dynamical masses are ∼2 × 108 M⊙ and 5.1 × 108 M⊙, respectively (adapted from Reakes 1980). Its gas-phase and stellar metallicities are estimated to be 12 + log(O/H) ∼ 8.3 (Calzetti et al. 1994; González Delgado et al. 1997; Kobulnicky & Skillman 1997) and Z ∼ 0.1–0.2 Z⊙ (Grocholski et al. 2008; Aloisi et al. 2001), respectively. Star formation has taken place in NGC 1569 for a Hubble time, although with different intensities as obtained by Vallenari & Bomans (1996), Greggio et al. (1998), Aloisi et al. (2001), and Angeretti et al. (2005) using color–magnitude diagrams of resolved stars. The recent studies by Angeretti et al. (2005) and Grocholski et al. (2008) show that the star formation activity of NGC 1569 started about 10 Gyr ago and proceeded until ∼1 Gyr ago presumably at a constant, very low rate. In the last 1 Gyr, however, NGC 1569 experienced at least three major bursts of star formation: (1) the older one started about 1 Gyr ago and ended ∼100 Myr ago with an average star formation rate (∼0.04 M⊙ yr−1), (2) the intermediate episode was triggered about ∼100 Myr ago and lasted up to 30 Myr ago with (∼0.08 M⊙ yr−1, and
(3) the younger burst began ~27 Myr ago and ended about 8 Myr ago with (SFR) ~0.3 $M_\odot$ yr$^{-1}$ (Angeretti et al. 2005). According to Aloisi et al. (2001), the spatial distribution of stars across the galaxy changes with their age, so that stars younger than 50 Myr are more centrally concentrated, intermediate-age stars (50 Myr–1 Gyr) are uniformly distributed, and older stars are mostly found in the outskirts of NGC 1569. Angeretti et al. (2005) suggested that this episodic star formation (in the last 1 Gyr) could be ascribed to the gravitational interactions of NGC 1569 with an H ii cloud ($\sim 7 \times 10^6 M_\odot$ in mass) a few kpc away yet connected to the galaxy by an H ii bridge (cf. Stil & Israel 1998).

The presence of several H ii regions (Waller 1991) and the spatially extended He emission indicates that NGC 1569 has formed new stars rather recently. Hunter & Elmegreen (2004) used the spatially integrated Hα luminosity (corrected for reddening) to derive an SFR of ~0.6 $M_\odot$ yr$^{-1}$ (adjusted to a distance of 3.36 Mpc). The morphology of the extended Hα is rather complex and characterized by arcs, filaments, and four large-scale superbubbles (Hunter et al. 1993; Heckman et al. 1995; Martin 1998; Westmoquette et al. 2008). The latter are seen to expand at typical velocities of ~100 km s$^{-1}$ which imply dynamical ages <25 Myr, consistent with the most recent burst of star formation derived by Angeretti et al. (2005; Heckman et al. 1995; Westmoquette et al. 2008). The expansion of these superbubbles is most likely powering a galactic outflow throughout the disk whose direction is approximately perpendicular to the inclined and flattened H ii disc of NGC 1569. The presence of an outflow of ionized gas is also supported by the high [S ii]/Hα ratios measured within the superbubbles and indicative of shocks (Westmoquette et al. 2008). The arcs of ionized gas detected in Hα and X-ray in the superbubbles suggest that the hot gas is still confined within the superbubbles, although it is moving at the escape velocity of NGC 1569. Thus, at present day, the galactic outflow of NGC 1569 does not appear to be in a steady state and to be able to induce mass loss from the galaxy (Westmoquette et al. 2008).

NGC 1569 is special also for another reason: it hosts two of the nearest superstar clusters (SSCs) known (SSCs A and B; Arp & Sandage 1985). SSCs are massive star clusters a few Myr to several hundred Myr old, believed to be the ancestors of globular clusters. In fact, they are as extended and massive as globular clusters and, after ~10 Gyr of passive evolution, they can match the luminosity range spanned by globular clusters today (cf. van den Bergh 1995; Meurer 1995). They are typically observed in interacting/merger systems (see Whitmore et al. 1993) and starburst galaxies (see Meurer et al. 1995). In NGC 1569, SSC A has been resolved into two components (A1 and A2; De Marchi et al. 1997), of which A2 may be the host of young O and Wolf-Rayet stars and A1 together with SSC B may be dominated by older red supergiants (Origlia et al. 2001). González Delgado et al. (1997) suggested that SSCs A and B have possibly undergone sequential star formation, with two major bursts of star formation about 3 and 9 Myr ago. The authors also found a deficit of ionized gas around SSCs A and B which may have been created by the stellar winds and supernova explosions of the older burst removing the local gas. According to the measurements of Ho & Filippenko (1996), SSC A is as massive as ~4 $\times 10^5 M_\odot$ (adjusted to a distance of 3.36 Mpc).

Age dating of star clusters and resolved stars strongly depends on dust extinction. Studies of the stellar content of NGC 1569 based on long-slit spectroscopy show that the intrinsic dust extinction varies across NGC 1569 by a few tenths of a dex, and peaks at SSCs A and B (González Delgado et al. 1997; Origlia et al. 2001) and in the northwest (NW) portion of the galaxy (Kobulnicky & Skillman 1997). The spatial coverage of long-slit spectroscopy is coarse, however, and no uniform and contiguous two-dimensional map of the dust extinction in NGC 1569 is available in the literature. Clearly, such a two-dimensional map helps us reach a higher accuracy in the determination of the star formation history and its associated SFR across NGC 1569. For this reason, we have taken advantage of the large field of view of LUCIFER mounted on the Large Binocular Telescope (LBT) to perform deep imaging in the Brγ filter and in the K band. Our aim is to construct the 2D spatial map of dust extinction across NGC 1569 from the Brγ and Hα (obtained with the Advanced Camera for Surveys (ACS) on the Hubble Space Telescope (HST) images of the galaxy and to derive the 2D spatial distribution of SFR density. We also observed the He i 1.08 μm and [Fe ii] 1.64 μm lines and their broadband continua in order to estimate the number of massive young stars and the supernova rate in NGC 1569, respectively. The observations and data reduction are described in Section 2. The spatial distribution of the color excess $E_{B-V}$ associated with the gas and the spatial distribution of the SFR density across NGC 1569 are derived in Sections 3 and 4, respectively, while the properties of the [Fe ii] 1.64 μm emission are analyzed in Section 5. Conclusions follow in Section 6.

2. OBSERVATIONS

The observations presented here were carried out with the LBT, located on Mount Graham, Arizona (Hill et al. 2006). NGC 1569 was observed during the science commissioning of LUCIFER (Ageorges et al. 2010; Seifert et al. 2010), with the N3.75 camera which provides a 4′ × 4′ field of view at an angular resolution of 0′′12 pixel$^{-1}$ (equivalent to 1.95 pc pixel$^{-1}$ at the adopted distance of 3.36 Mpc). We imaged NGC 1569 between 2009 September and November in the $JHK$ broad bands and in the narrowband He i 1.08 μm, [Fe ii] 1.64 μm, and Brγ filters, with a seeing $\leq$0′′5 (i.e., 8 pc) throughout the observing runs. Although the exposure times in the broadband and Brγ filters were estimated from the available Two Micron All Sky Survey (2MASS) photometry and HST/ACS F658N (Hα) image via the LUCIFER Exposure Time Calculator, the effective exposure times were largely dictated by the available amount of time during the LUCIFER commissioning. The exposure time for each of the He i 1.08 μm and [Fe ii] 1.64 μm filters was set to 1 hr (following Labrie & Pritchet 2006), but it was later cut down to 30 minutes for the He i 1.08 μm. The final exposure times on source achieved for the near-IR data set are listed in Table 1, together with the imaging taken in the F606W (broad V) and F658N (Hα) filters with HST/ACS as part of program ID 10885 (PI: Aloisi).

### Table 1

| Filter | Exposure Time (minutes) |
|--------|-------------------------|
| J      | 20                      |
| H      | 55                      |
| K      | 121                     |
| He i 1.08 μm | 30                  |
| [Fe ii] 1.64 μm | 67                |
| Brγ    | 111                     |
| F606W  | 326                     |
| F658N  | 77                      |
The near-IR images were reduced with standard IRAF\(^8\) routines. They were corrected for bias and flat fielding, and their astrometric solution was derived from the field stars in common with 2MASS. After background subtraction, the images taken in the same filter were corrected for geometric distortion and then combined together on the basis of their World Coordinate System with a weighted mean. The final mosaicked frames in the broadband filters were flux calibrated, at a 10\% accuracy, using the 2MASS magnitudes of the stars in the field of NGC 1569.

After convolution to the same point spread function (PSF) (FWHM = 0.5), the continuum emission was subtracted from each narrowband image by scaling the closest broadband image \((J \text{ for } \text{H} \alpha \ 1.08 \mu\text{m}, H \text{ for } \text{[Fe} \ ii \] \ 1.64 \mu\text{m}, \text{and } K \text{ for Br} \gamma) so that field stars would have had the same integrated count rate in both the narrowband and broadband filters. This scaling was applied to the broadband zero points in order to calibrate the pure emission line images in flux, with an achieved accuracy of 20\% (estimated from the scatter in the zero point derived from different stars).

The optical HST/ACS images were retrieved from the HST archive already reduced. The subtraction of the continuum emission (the F606W image) from the F658N frame and the flux calibration of the pure H\(\alpha\) emission were performed as for the near-IR data, reaching a flux accuracy of 20\%. Such a low accuracy in the flux calibration of the H\(\alpha\) is mostly due to the broad F606W filter which makes it impossible to account of flux ratios in different passbands. In order to ensure a 1% accuracy, we apply Equation (1) to each pixel in the observed H\(\alpha\) and Br\(\gamma\) frames in order to derive the spatial distribution of \(E_{\text{g}}(B-V)\) (intrinsic + foreground) across NGC 1569. This is shown in Figure 2; we clearly see that the color excess is higher

\[E_{\text{g}}(B-V) = \frac{-0.4\log(R_{\text{obs}}/R_{\text{int}})}{\kappa(\text{H}\alpha) - \kappa(\text{Br}\gamma)}\]  

\(^8\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
(>0.6 mag) where the H and He emission fluxes are higher, and the NW half of the galaxy is more extinguished than the southeast (SE), where $E_g(B-V) < 0.6$ mag. The distribution of the pixel color excess as derived from Figure 2 peaks at about $E_g(B-V) = 0.6$ mag and its FWHM points to variations in $E_g(B-V)$ up to 0.4 mag across the galaxy. The presence of a gradient in $E_g(B-V)$ along the galaxy major axis is evident in Figure 3, where we plot the azimuthal $E_g(B-V)$ as a function of position along the semimajor axis of NGC 1569. From now on, we assume the convention of negative distances for increasing right ascension from the galaxy center. The vertical error bar (±0.1 dex) in Figure 3 indicates the systematic uncertainty on $E_g(B-V)$ due to the uncertainty on the flux calibration. Because of our S/N cut, the color excess can be determined only for galactocentric distances $< -50$ pc and $> 30$ pc. As Figure 3 shows, the color excess increases from $E_g(B-V) \approx 0.57$ mag in the SE portion of the galaxy to $E_g(B-V) = 0.7–0.8$ mag in the NW. This gradient
is consistent with the findings of Kobulnicky & Skillman (1997). The higher $E_g(B - V)$ (~0.7) seen at +100 pc from the central cavities in Figure 3 is in agreement with the findings of González Delgado et al. (1997).

We use the 2D spatial map of $E_g(B - V)$ to correct the line-emission images pixel-by-pixel following the formula:

$$F_i(\lambda) = F_0(\lambda) \times 10^{0.4 E_g(B-V) \kappa(\lambda)},$$

(2)

where $F_i(\lambda)$ and $F_0(\lambda)$ are the intrinsic and observed line flux, respectively, and $\kappa(\lambda)$ is the extinction law. For a Fitzpatrick's (1999) extinction curve, $\kappa$ is 2.535, 1.096, 0.562, and 0.363 for Hα, He I 1.083 μm, [Fe II] 1.64 μm, and Brγ, respectively (D. Calzetti 2010, private communication). The correction for dust extinction enables us to correct the [Fe II] 1.64 μm emission for the contribution of the Br12 line, estimated to be 0.17 times the Brγ flux (assuming Case B; Storey & Hummer 1995). We then compute the surface brightness profile of NGC 1569 for concentric, elliptical, semi-annuli of fixed ellipticity ($b/a = 0.45$) and fixed orientation of the semimajor axis (P.A. = 117°) in each filter. These profiles are shown in Figure 4 where the surface brightness is corrected for reddening but not for the galaxy inclination. The gap in the line-emission profiles between ~50 and 30 pc is due to our S/N cut which masked out the central, gas-deficient regions. The surface-brightness profiles of the H and He lines share a similar shape, with maxima at a galactocentric distance of about ±300 pc. At smaller galactocentric distances the surface brightness of the H and He lines declines, while that of the [Fe II] line stays constant and is ~0.6 dex brighter than Brγ. At galactocentric distances <−300 pc and >300 pc, all five profiles are close to an exponential disk with similar scale lengths. All profiles appear to be steeper in the NW half of the galaxy with a typical, exponential scale length of 70 pc against 90 pc as measured for the SE half. The peak at ~550 pc in the [Fe II] surface brightness is due to the emission from a compact SNR.

4. THE RECENT STAR FORMATION ACTIVITY OF NGC 1569

We integrate the dereddened Hα, He I 1.08 μm, and Brγ maps of NGC 1569 over an ellipse of semimajor axis $a = 37^\prime$ (606 pc) and semiminor axis $b = 17^\prime$ (274 pc) which does not include the extended Hα superbubbles. Pixels below our S/N cut are excluded from the integration. We obtain a total, dereddened luminosity of $5.31 \times 10^{39}$ erg s$^{-1}$ (±0.20 dex), $4.51 \times 10^{39}$ erg s$^{-1}$ (±0.14 dex), and $5.05 \times 10^{38}$ erg s$^{-1}$ (±0.11 dex) for the Hα, He I 1.08 μm, and Brγ lines, respectively, at the adopted distance of 3.36 Mpc. The quoted uncertainties (all at 1σ level) are due to flux calibration and reddening correction. We use these values to study the stellar population responsible for ionizing the interstellar H and He, and the dereddened Hα and Brγ images to trace the spatial distribution of the SFR density across NGC 1569.

4.1. The Recent Starburst

We compute the relation between the number of ionizing photons [$Q(H^0)$] for hydrogen and the Hα (Brγ) line luminosity, as well as the relation between the number of ionizing photons [$Q(He^0)$] for helium and the He I 1.08 μm line luminosity, under Case B with a temperature of 10,000 K and a density of 100 cm$^{-3}$ (typical of H ii regions):

$$Q(H^0) (s^{-1}) = 7.3 \times 10^{11} L(H\alpha) (\text{erg s}^{-1})$$

(3)

$$Q(He^0) (s^{-1}) = 7.5 \times 10^{12} L(\text{Br}\gamma) (\text{erg s}^{-1})$$

(4)

$$Q(He^0) (s^{-1}) = 1.0 \times 10^{14} L(1.08 \mu m) (\text{erg s}^{-1})$$

(5)

Applying Equations (3)–(5) to the total, dereddened luminosities from above yields $Q(H^0) = 3.88 \times 10^{52}$ s$^{-1}$ from the Hα line, $Q(H^0) = 3.79 \times 10^{52}$ s$^{-1}$ from the Brγ line, and $Q(He^0) = 4.51 \times 10^{51}$ s$^{-1}$. In Figure 5, we compare $Q(H^0)$ (as derived from the Brγ line) and $Q(He^0)$ with STAR-BURST99 (Leitherer et al. 1999) predictions for an instantaneous burst of star formation (panel (a)) and for continuous star formation (panel (b)). For both scenarios, we adopted $Z = 0.2 Z_\odot$ and a Kroupa (2001) initial mass function (with exponents = 1.3 and 2.3 for the mass ranges 0.1–0.5 $M_\odot$ and 0.5–100 $M_\odot$, respectively); stellar evolution was modeled with the Geneva evolutionary tracks for high mass-loss rates (Meynet et al. 1994). In panel (a) of Figure 5, the correlation between $Q(H^0)$ and $Q(He^0)$ for different stellar ages and at fixed total mass ($M_{\text{tot}}$) of the burst is traced by solid lines corresponding to $M_{\text{tot}}$ = 10$^5$, 10$^6$, and 10$^7$ $M_\odot$. The dashed lines represent the correlation between $Q(H^0)$ and $Q(He^0)$ for different $M_{\text{tot}}$ and at fixed stellar age ($1, 3, 5,$ and 7 Myr). The number of H and He ionizing photons measured for NGC 1569 from its Brγ and He I 1.08 μm lines is plotted with a black-filled circle whose error bars (±1σ) take into account the systematic uncertainty due to flux calibration and reddening correction. This number is consistent with being produced by a 4 Myr (±0.3 Myr at 1σ level) old stellar population, comprising ~5400 O stars and ~250 Wolf-Rayet stars and with a total mass of 1.8 × 10$^6$ $M_\odot$ (with a 20% uncertainty, at 1σ level). In panel (b), the observed values of $Q(H^0)$ and $Q(He^0)$ are compared with the predictions for continuous star formation: the solid lines show the correlation between $Q(H^0)$ and $Q(He^0)$ at fixed SFRs of 0.05, 0.10, 0.15, and 0.20 $M_\odot$ yr$^{-1}$, and their length...
spans the time interval between 1 Myr and 1 Gyr. At stellar ages older than 1 Gyr, Q(Hα) and Q(HeⅡ) cease to change with time. None of the tracks fits within 1σ the number of H and He ionizing photons measured for NGC 1569; the observed Q(Hα) and Q(HeⅡ) are marginally consistent with a star formation history with SFR > 0.15 \( M_\odot \) yr\(^{-1}\) that has been going on for more than 10 Myr.

We checked whether the properties of the stellar population ionizing the H and He gas in NGC 1569 vary with galactocentric distance. We integrated the flux of the dereddened Hα and HeⅠ 1.083 \( \mu \)m images over concentric, elliptical semi-annuli and derived the corresponding Q(Hα) and Q(HeⅡ) as a function of galactocentric distance. We compared these Q(Hα) and Q(HeⅡ) values with the SB99 predictions for instantaneous bursts and found that stellar ages are consistent with a value of \(~4\) Myr at any galactocentric distance. On the other hand, the mass surface density of the ionizing stars increases inward, from \(~0.01 M_\odot \) pc\(^{-2}\) at \pm 700 pc from the galaxy center to \(~0.3 M_\odot \) pc\(^{-2}\) at 300 pc in the SE portion of NGC 1569 and to \(~1.8 M_\odot \) pc\(^{-2}\) in the NW.

4.2. The Star Formation Rate and Its Density

Using the relation between SFR and the dereddened Hα (or Brγ) luminosity as in Kennicutt (1998), we derive an average SFR of \(\approx 0.4 M_\odot\) yr\(^{-1}\), consistent with what can be inferred from the age and total mass of the burst derived above. The uncertainty on the flux calibration of both emission lines and on the reddening determination gives rise to a systematic uncertainty of ±0.20 dex on the SFR derived from the Hα (or 0.11 dex on the SFR estimated from the Brγ).

The 2D map of the SFR per pixel, obtained from the dereddened Brγ image, is shown in Figure 6 in logarithmic units; the SFR across NGC 1569 is typically \(\approx 10^{-6} M_\odot\) yr\(^{-1}\) pixel\(^{-1}\) (i.e., \(3 \times 10^{-7} M_\odot\) yr\(^{-1}\) pc\(^{-2}\)) and increases to few \(10^{-5} M_\odot\) yr\(^{-1}\) pixel\(^{-1}\) (i.e., \(\approx 10^{-3} M_\odot\) yr\(^{-1}\) pc\(^{-2}\)) at each side of the cavities where the H and He line emissions peak. This trend is well described by the azimuthal SFR density (obtained by integrating the dereddened flux of the Brγ image over concentric, elliptical semi-annuli) plotted as a function of position along the semimajor axis (see Figure 7). The maxima of the SFR density are about \(9 \times 10^{-7} M_\odot\) yr\(^{-1}\) pc\(^{-2}\) and \(4 \times 10^{-6} M_\odot\) yr\(^{-1}\) pc\(^{-2}\) at \pm 300 pc and +300 pc from the galaxy center, respectively. The error bars \((\pm 1\sigma)\) in Figure 7 indicate a systematic uncertainty of ±0.1 dex on the SFR derived from the dereddened Brγ image.

The width of the distribution of the pixel SFR as obtained from the dereddened Brγ image indicates that SFR density varies by a factor of 10 within the galaxy.

5. THE [Fe ii] EMISSION

The [Fe ii] emission, with its prominent lines at 1.26 \( \mu \)m and 1.64 \( \mu \)m, is usually explained as triggered by electron collisions occurring in a zone of partially ionized hydrogen where Fe\(^{+}\) and e\(^-\) coexist. The emission intensity is proportional to the size of this region, which is rather small in H\(^{\prime}\) regions but extended in SNRs (cf. Oliva et al. 1989). The [Fe ii] emission would thus be a clear signpost for SNRs, and as such it is expected to come from compact sources in external galaxies. Recent studies have shown that the [Fe ii] emission can also be spatially extended in galaxies known to experience a galactic wind (e.g., NGC 253: Forbes et al. 1993; Sugai et al. 2003;
NGC 5253: Cresci et al. 2010; Labrie & Pritchet 2006; Turner et al. 2000; M 82: Greenhouse et al. 1997; Heckman et al. 1987. Some theoretical computations (e.g., Seab & Shull 1983 and McKee et al. 1987) have shown that this extended [Fe ii] emission can be explained by high-speed shocks such as those associated with a galactic outflow. The proposed mechanism assumes that iron atoms can be extracted from silicate grains that are preferentially destroyed via nonthermal sputtering and grain–grain collisions (cf. also McCarthy et al. 1987; van der Werf et al. 1993. We note that these mechanisms can also be triggered by SN shocks). NGC 1569 is yet another starburst galaxy exhibiting spatially extended emission of [Fe ii] 1.64 μm (already detected by Labrie & Pritchet) and a galactic outflow (Heckman et al. 1995).

Given that the Brγ emission comes from gas ionized by OB stars, the flux ratio [Fe ii] 1.64 μm/Brγ is commonly used to trace the number ratio of supernovae (SNe) to OB stars, hence the star formation history of a galaxy at fixed initial mass function. Values of this ratio larger than few tens indicate that excitation is mostly produced by SN shocks, while values ≲1, typically 0.1 or lower, are due to photoionization (Alonso-Herrero et al. 1997). The dereddened [Fe ii] 1.64 μm luminosity (already corrected for the emission of the Br12 line) integrated over an ellipse of the semimajor axis $a = 37''$ and the semiminor axis $b = 17''$ (excluding the central cavities) is $4.67 \times 10^{38}$ erg s$^{-1}$ at the adopted distance of 3.36 Mpc. From this and the integrated luminosity of Brγ, we obtain a global [Fe ii] 1.64 μm/Brγ ratio = 0.9, suggesting that excitation by SN shocks may prevail over photoionization by OB stars formed during the most recent burst. Figure 8 shows the two-dimensional spatial distribution of the [Fe ii] 1.64 μm/Brγ ratio across NGC 1569. The line ratio is larger than 1 mainly in the galaxy outskirts and around the central cavities, and it is <1 especially in two regions at the opposite extremes of the cavities coincident with the peaks of the Hα emission and the SFR density. Another way of looking at the spatial variation of the [Fe ii] 1.64 μm/Brγ ratio is to integrate the dereddened flux of the [Fe ii] 1.64 μm and Brγ images over concentric, elliptical semi-annuli and compute the [Fe ii] 1.64 μm/Brγ flux ratio as a function of position along the semimajor axis. This is plotted in Figure 9; the minima at [Fe ii] 1.64 μm/Brγ < 1 occur at about ±300 pc from the galaxy center where the SFR density is highest (cf. Figure 8). The peak at ~550 pc is due to a compact SNR. The [Fe ii] 1.64 μm/Brγ ratio increases above 1 with galactocentric distance and at the edges of the cavities, possibly suggesting that in these regions star formation has been somehow quenched. A relevant caveat on this last interpretation comes from the possibility that iron has been excited by shocks produced by the galactic outflow of NGC 1569. In this case, the [Fe ii] 1.64 μm/Brγ ratio may be expected not to trace the star formation history of a galaxy on small spatial scales. The extent by which a galactic outflow can alter this ratio so that it is no longer representative of the local number ratio SNe versus OB stars is still to be thoroughly investigated. In their spectroscopic study of the central 20'' × 20'' in NGC 1569, Westmoquette et al. (2007) found little evidence for shocked line ratios, most likely because this area is experiencing intense star formation and photoionization from OB stars. In this region (equivalent to about 320 × 320 pc$^2$ at the adopted distance of 3.36 Mpc), we measure the lowest values of [Fe ii] 1.64 μm/Brγ (see Figure 9; exception made for the cavities edge), which may also be interpreted as due to photoionization.

We used the dereddened, integrated luminosity of the [Fe ii] 1.64 μm and Brγ lines to estimate the supernova rate and the gas-phase abundance of Fe$^+$ for NGC 1569 as a whole. Under the assumption that the typical [Fe ii] 1.64 μm luminosity of a supernova is $\sim 10^{37}$ erg s$^{-1}$ and its average life $\sim 10^4$ yr (cf. Lumsden & Puxley 1995), we estimate an SNR of $\sim 0.005$ yr$^{-1}$ for the whole galaxy. As for the gas-phase abundance of Fe$^+$, we adopt Greenhouse et al.’s (1997) prescription, where

$$\frac{N(Fe^+)}{N(H)} \sim 9 \times 10^{-6} \frac{L(\text{[Fe II] 1.64})}{L(\text{Paβ})}$$  

(6)

under Case B for a temperature of 10,000 K and a density of 100 cm$^{-3}$. For the same physical conditions, $L(\text{Paβ}) = 5.86 L(\text{Brγ})$, hence

$$\frac{N(Fe^+)}{N(H)} \sim 1.54 \times 10^{-6} \frac{L(\text{[Fe II] 1.64})}{L(\text{Brγ})}.$$  

(7)
dominates over photoionization from OB stars and indicate that star formation has been quenched some Myr ago in the central cavities and in the outermost regions of the galaxy. This trend would be consistent with the findings of Aloisi et al. (2001), whereby the age of stars increases with galactocentric distance from 50 Myr close to the galaxy center to >1 Gyr in the galaxy outskirts. How and to which extent the intervention of a galactic outflow as in NGC 1569 alters the [Fe ii] 1.64 μm/Bry ratio and prevents it from tracing the ISM excitation mechanisms on small spatial scales remains to be fully investigated. On global scales, the [Fe ii] 1.64 μm luminosity integrated over the galaxy main body points to an SN rate of about 0.005 yr⁻¹ and an iron abundance N(Fe⁺)/N(H) ≥ 1.4 × 10⁻⁶. This value is quite consistent with the Fe abundance in the ISM of the Small Magellanic Cloud (SMC; Rolleston et al. 2003). If the high-speed shocks in the galactic outflow would be responsible for extracting iron atoms from silicate grains (as suggested by the theoretical calculations of, for example, Seab & Shull 1983 and McKee et al. 1987) and hence for a spatially extended [Fe ii] emission, one would expect to find the ISM Fe abundance in NGC 1569 to be enhanced with respect to the SMC which has a stellar metallicity similar to NGC 1569 but no galactic outflow. Given that the ISM Fe abundance is similar in both NGC 1569 and the SMC, the present data would tend to exclude that the diffuse [Fe ii] emission in NGC 1569 is due to the galactic outflow. Moreover, Sofia et al. (2006) found that iron atoms in the ISM of the SMC are most likely locked in metal grains and/or oxides rather than in silicates. If this applied to NGC 1569 also, the galactic outflow would not be able to extract iron from dust grains (as in the scenario proposed by Seab & Shull 1983 and McKee et al. 1987), increase the Fe emission, and thus explain its spatial extension.

We used the Hα, Bry, and He i 1.08 μm luminosities integrated over NGC 1569 to estimate the SFR of the most recent burst (≈0.4 M⊙ yr⁻¹) and the number of stellar photons able to ionize the interstellar H and He gas [i.e., Q(H) and Q(He)]. When compared to STARBURST99 predictions, the observed Q(H) and Q(He) enable us to constrain the age and the mass of the stellar population responsible for ionizing H and He. In the case of NGC 1569, the values of Q(H) and Q(He) are in good agreement with an instantaneous burst of star formation. A scenario where star formation is continuous and takes place with a constant SFR is not rejected by statistics, but is seemingly inconsistent with the gaseous nature of the star formation activity undergone by NGC 1569 in the last 1 Gyr, as derived by Angeretti et al. (2005) from the color–magnitude diagram of resolved stars. The best-fitting instantaneous burst occurred about 4 Myr ago and involved a total stellar mass of ≈1.8 × 10⁶ M⊙. It gave birth to about 5400 O stars and 250 Wolf-Rayet stars. Such a stellar age is constant with galactocentric distance and where Hα, Bry, and He i 1.08 μm emissions are detected. The only property of the burst changing with distance from the galaxy center is the surface mass density of the ionizing stars, which follows the surface brightness profiles of the H and He lines and increases from ≈0.01 M⊙ pc⁻² in the galaxy outskirts up to ≈1.8 M⊙ pc⁻² just outside the central cavities. The comparison of this latest starburst with the three episodes of star formation identified by Angeretti et al. (2005; cf. Section 1) suggests a star formation history where the burst duration and average SFR have become shorter and larger, respectively, from 1 Gyr ago to 4 Myr ago. Consequently, the total mass in stars produced by these bursts of star formation has decreased by a factor of about 20 in the last 1 Gyr. Interestingly enough, the 4 Myr age derived

6. CONCLUSIONS

The wide field of view and high angular resolution of the infrared imager/spectrograph LUCIFER mounted on the LBT allowed us to acquire deep and detailed images of the local starburst NGC 1569 in the He i 1.08 μm, [Fe ii] 1.64 μm, and Bry light. Together with HST/ACS Hα images of the galaxy, these data were used to derive the two-dimensional spatial distributions (on scales as small as 2 pc) of dust extinction (foreground + intrinsic), SFR density, and [Fe ii] 1.64 μm/Bry ratio, and to estimate the age and total mass of the most recent burst responsible for ionizing the ISM in NGC 1569. The galaxy looks clearly asymmetric along its major axis with respect to its center, where its SSCs A and B have most likely evacuated gas and formed gas-deficient cavities. The color excess E(B −V) = 0.57 mag and increases to 0.7-0.8 mag in the NW along the galaxy major axis. Similarly to the surface brightness profiles of the H and He line emissions, the SFR density increases inward along the major axis, reaching two maxima of 9 × 10⁻⁷ and 4 × 10⁻⁶ M⊙ yr⁻¹ pc⁻² at ~300 and +300 pc, respectively, from the galaxy center (i.e., just outside the central cavities). Within the galaxy, the SFR density is seen to vary by a factor of 10. The peaks in SFR density are spatially coincident with the minima in the [Fe ii] 1.64 μm/Bry flux ratio, suggesting that the OB stars formed during the most recent burst are responsible for the ISM photoionization and are preferentially located in a ring around the central cavities. The [Fe ii] 1.64 μm/Bry ratio is seen increasing outward from the galaxy center and along its major axis, as well as at the edges of the central cavities. At face value, this trend may imply that excitation by SN shocks

We thus derive N(Fe⁺)/N(H) ≥ 1.4 × 10⁻⁶ and N(Fe)/N(Fe) ≥ 0.05, where the Sun N(Fe)/N(H) is 2.8 × 10⁻⁵ (Holweger 2001). The lower limit comes from the assumption that all the iron is singly ionized.

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from the observed \( Q(\text{H}^0) \) and \( Q(\text{He}^0) \) is close to that of the younger stellar component found mostly in SSC A by González Delgado et al. (1997). Therefore, the big picture emerging from these results is one where the strong stellar winds and supernova explosions from the older stellar population of SSCs A and B (about 9 Myr old) removed a large fraction of gas from the cluster surroundings and triggered, ∼4 Myr later, star formation at the edges of the central cavities. The gas left over in the vicinity of SSC A (and perhaps also B) underwent star formation nearly at the same time.

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REFERENCES

Ageorges, N., et al. 2010, Proc. SPIE, 7735, 77351L
Aloisi, A., et al. 2001, AJ, 121, 1425
Alonso-Herrero, A., Rieke, M. J., Rieke, G. H., & Ruiz, M. 1997, ApJ, 482, 747
Angeretti, L., Tosi, M., Greggio, L., Sabbidi, E., Aloisi, A., & Leitherer, C. 2005, AJ, 129, 2203
Arp, H., & Sandage, A. 1985, MPA Rep., 173, 29
Broadhurst, T., Ellis, R., & Glazebrook, K. 1992, Nature, 355, 55
Burstein, D., & Heiles, C. 1982, AJ, 87, 1165
Calzetti, D., Kinney, A., & Storchi-Bergmann, T. 1996, ApJ, 458, 132
Cole, S., Aragón-Salamanca, A., Frenk, C. S., Navarro, J. F., & Zepf, S. E. 1994, MNRAS, 271, 781
Cresci, G., Vanzetti, L., Sauvage, M., Santangelo, G., & van der Werf, P. 2010, A&A, 520, 82
De Marchi, G., Clampin, M., Greggio, L., Leitherer, C., Nota, A., & Tosi, M. 1997, ApJ, 479, L27
Fitzpatrick, E. L. 1999, PASP, 111, 63
Forbes, D., Ward, M. J., Rotaciuc, V., Blietz, M., Genzel, R., Drapatz, S., van der Werf, P. P., & Krabbe, A. 1993, ApJ, 406, L11
González Delgado, R. M., Leitherer, C., Heckman, T., & Cerviño, M. 1997, ApJ, 483, 705
Greenhouse, M. A., et al. 1997, ApJ, 476, 105
Greggio, L., Tosi, M., Clampin, M., De Marchi, G., Leitherer, C., Nota, A., & Sirianni, M. 1998, ApJ, 504, 725
Grocholski, A. J., et al. 2008, ApJ, 686, L79
Heckman, T. M., Armus, L., McCarthy, P., van Breugel, W., & Miley, G. K. 1987, in Proc. Conf. on Star Formation in Galaxies, ed. C. J. Lonsdale Persson (SEE N87-24266 17-89), 461
Heckman, T. M., Dahlem, M., Lehmer, M. D., Fabbiano, G., Gilmore, D., & Waller, W. H. 1995, ApJ, 448, 98
Hill, J. M., Green, R. F., & Slagle, J. H. 2006, Proc. SPIE, 6267, 62670Y
Ho, L. C., & Filippenko, A. V. 1996, ApJ, 466, L83
Holweger, H. 2001, in AIP Conf Proc. 598, Solar and Galactic Composition: A Joint SOHO/ACE Workshop (Melville, NY: AIP), 23
Hunter, D. A., & Elmegreen, B. G. 2004, AJ, 128, 2170
Hunter, D. A., Hawley, W. N., & Gallagher, J. S., III. 1993, AJ, 106, 1797
Izotov, Y. I., & Thuan, T. X. 1999, ApJ, 511, 639
Kauffmann, G., White, S. D. M., & Guiderdoni, B. 1993, MNRAS, 264, 201
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Kobulnicky, H. A., & Skillman, E. D. 1997, ApJ, 489, 636
Kroupa, P. 2001, MNRAS, 322, 231
Labrie, K., & Pritchett, C. J. 2006, ApJS, 166, 188
Leitherer, C., et al. 1999, ApJS, 123, 3
Lilly, S. S. J., Tresse, L., Hammer, F., Crampton, D., & Le Fevre, O. 1995, ApJ, 455, 108
Lumsden, S. L., & Peyley, P. J. 1995, MNRAS, 276, 723
Martin, C. L. 1998, ApJ, 506, 222
McCarthy, P. J., Heckman, T. M., & van Breugel, W. 1987, AJ, 93, 264
McKee, C. F., Hollenbach, D. J., Seab, C. G., & Tielens, A. G. G. M. 1987, ApJ, 318, 674
Meurer, G. 1995, Nature, 375, 742
Meurer, G., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. 1995, AJ, 110, 2665
Meynet, G., Maeder, A., Schaller, D., & Charbonnel, C. 1994, A&AS, 103, 97
Moustakas, J., & Kennicutt, R. C., Jr. 2006, ApJS, 164, 81
Oliva, E., Moorwood, A. F., & Danziger, I. J. 1989, A&A, 214, 307
Origlia, L., Leitherer, C., Aloisi, A., Greggio, L., & Tosi, M. 2001, AJ, 122, 815
Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley, CA: Univ. Science Books)
Reakes, M. 1980, MNRAS, 192, 297
Rolleston, W. R. J., Venn, K., Tolstoy, E., & Dufton, P. L. 2003, A&A, 400, 21
Seab, C. G., & Shull, J. M. 1983, ApJ, 275, 652
Seifert, W., et al. 2010, Proc. SPIE, 7735, 77357W
Soña, U. J., Gordon, K. D., Clayton, G. C., Misselt, K., Wolff, M. J., Cox, N. L. J., & Ehrenfreund, P. 2006, ApJ, 636, 753
Stil, J. M., & Israel, F. P. 1998, A&A, 337, 64
Storey, P. J., & Hummer, D. G. 1995, MNRAS, 272, 41
Sugai, H., Davies, R. I., & Ward, M. J. 2003, ApJ, 584, 9
Turner, J. L., Beck, S. C., & Ho, P. T. P. 2000, ApJ, 532, 109
Vallenari, A., & Bomans, D. J. 1996, A&A, 313, 713
van den Bergh, S. 1995, Nature, 374, 215
van der Werf, P. P., Genzel, R., Krabbe, A., Blietz, M., Lutz, D., Drapatz, S., Ward, M. J., & Forbes, D. A. 1993, ApJ, 405, 522
Waller, W. H. 1991, ApJ, 370, 144
Westmoquette, M. S., Smith, L. J., & Gallagher, J. S., III. 2008, MNRAS, 383, 864
Westmoquette, M. S., Smith, L. J., & Gallagher, J. S., III, & Exter, K. M. 2007, MNRAS, 381, 913
White, S. D. M., & Frenk, C. S. 1991, ApJ, 379, 52
Whitmore, B. C., et al. 1993, AJ, 106, 1354
Zibetti, S. 2009, A&A, submitted (arXiv:0911.4956)
Zibetti, S., Charlot, S., & Rix, H.-W. 2009, MNRAS, 400, 1181