A detailed study of the post-starburst galaxy NGC 1569

I. Global parameters and starburst properties

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Summary. UV and infrared flux observations of the peculiar dwarf galaxy NGC 1569 are combined with literature data. The UV data show that NGC 1569 suffers considerable foreground extinction $E(B-V) = 0.56 \pm 0.10$; this suggests true distance modulus $(m-M)_0 = 26.7 \pm 0.6$, hence a distance of $2.2 \pm 0.6$ Mpc, which is considerably closer than previously assumed. The UV and optical data, together with a distance of $2.2$ Mpc imply an integrated stellar luminosity of $1.2 \pm 0.3 \times 10^9 L_\odot$. About 60% of the total stellar luminosity is reradiated in the far-infrared. The extinction-corrected UV colours are those of an evolved OB star population. The intrinsic UV, $U-B$, $B-V$ and $V-K$ colours show that NGC 1569 has undergone a burst of star formation (burst strength 3%-5%) characterized by star formation rates $dM/dt = 0.3 M_\odot$ yr$^{-1}$ about 1-2$\times$10$^7$ years ago. NGC 1569 presently shows the aftermath of this burst: it appears to be in the transition from a starburst phase to a quiescent phase. The duration of this transition phase is of order 10$^7$ yr. If the recent burst was typical for the star formation history of NGC 1569, some 25 bursts must have occurred in the past on average at intervals of $6 \times 10^8$ yr. In that case, NGC 1569 has spent about 5% of its lifetime in an active phase. This result suggests that most 'starburst' galaxies selected by their optical colours are, in fact, post-starburst galaxies.

Key words: galaxies: dwarf galaxies - star formation burst - UV observations: galaxies - star formation - infrared observations: galaxies

1. Introduction

This is the first in a series of papers on the peculiar irregular dwarf galaxy NGC 1569 also known as Arp 210 and VII Zw 16. In an attempt to clarify the behaviour and nature of this peculiar galaxy (Hodge, 1974; De Vaucouleurs et al., 1974), we have started a detailed study of NGC 1569 at optical and radio wavelengths, supplemented by ultraviolet and infrared observations. The purpose of the present paper is to serve as an introduction to this study. We present new ultraviolet and infrared data, and re-examine the literature to obtain a homogeneous set of global parameters for NGC 1569, and in particular the characteristics of its recent burst of star formation. This discussion will serve as a basis for the interpretation of the more detailed radio and optical observations which will be discussed in subsequent papers.

2. Observational history

NGC 1569 was first described by Herschel (1789) and subsequently by Reimnath (1926) and Baade (1931) as a Magellanic-type galaxy (see also De Vaucouleurs et al., 1976). Early spectroscopy was obtained by Mayall (1935) and Humason et al. (1956), who showed that NGC 1569 should be relatively close to the Galaxy (radial velocity of order 40 km s$^{-1}$). Photometric observations were published by Pettit (1954) and Holmberg (1958), but it was Ables (1971) who published the first thorough optical study of the object. In particular, he drew attention to two blue stellar objects A and B, seen against the nebula. They have $B = 15.7$ and $B = 16.5$, and $B-V = 0.6$ and $B-V = 0.4$, respectively. Ables tended to the conclusion that they are foreground stars, but did not exclude the possibility that they belong to NGC 1569, in which case they would intrinsically be very luminous.

The very irregular structure of NGC 1569 was first noted by Zwicky (1971) after Butslov et al. (1962) had already drawn attention to a peculiar Hz 'arm' in the SW of the galaxy. Renewed interest in NGC 1569 was triggered by a paper by Hodge (1974) who published Hz images of different exposure times clearly showing the filamentary nature of the galaxy, as well as the high intensity of the Hz emission. De Vaucouleurs et al. (1974) published an Hz velocity field (later updated by De Vaucouleurs, 1981) and considered an explosive event about 10$^7$ years ago, centered on objects A and B to be the most likely explanation for their observations.

The first high resolution aperture synthesis radio continuum maps were published by Seaquist and Bignell (1976). The maps were obtained with the NRAO three-element interferometer and showed thermal emission from several large H II region complexes in NGC 1569. The maps were used by Israel (1980) to determine the properties of the brightest H II regions and to derive a high star formation rate. A more recent VLA map of NGC 1569 with 6" resolution was published by Condon (1983). NGC 1569 was included in the dwarf galaxy survey carried out by Hunter (Hunter et al., 1982; Hunter, 1982) who found very blue intrinsic colours (see Sect. 3.2), as well as a low metallicity, in between those of LMC and SMC H II regions (cf. Dufour et al., 1982; also Sect. 4.3) and confirmed the high star formation rate. X-ray emission from NGC 1569 was detected with the Einstein Observatory by Fabbiano et al. (1982) who found a rather bright, resolved source roughly at the position of maximum optical and radio brightness (i.e. close to the position of objects A and B).

A relatively low-resolution (2") H I map was obtained by Reakes (1980) with the Cambridge Half-Mile Telescope. He
found a regular overall velocity field, and derived neutral hydrogen and total masses. Young et al. (1984) detected a weak $^{13}$CO(1–0) signal which they interpreted as an indication that NGC 1569 contains unusually little molecular hydrogen (but see Sect. 4.3).

Finally, Arp and Sandage (1985) returned to the question of the nature of objects A and B. They conclude that the optical spectra of both objects resemble a combination of A2 and B0 supergiant spectra, and discuss the possibility that A and B are nearby double stars with $(m-M)=23$, but favour the possibility that A and B are compact, luminous ‘super’ star clusters with $M_\ast = -13$.

From the cited literature, NGC 1569 has emerged as a small, relatively nearby irregular galaxy, extremely bright in Hα and very blue in broadband photometry. It has a low mass, but at least recently a very high star formation rate. Both its low metallicity and its star formation rate per unit mass show that recent star formation rates were much higher than the average star formation rate in the past. Thus, NGC 1569 must have experienced a strong burst of star formation not too long ago. The discovery that the nonthermal radio emission from NGC 1569 is significantly influenced by synchrotron radiation losses, implying a recent decrease in relativistic electron injection rates supports this conclusion (Israel and De Bruyn, 1988). The filamentary structure, and significant deviations from the overall velocity field seen in Hα point to a sizeable energetic event in the recent past. Prime candidates for the source of this event are objects A and B.

3. The global spectrum of NGC 1569

3.1. UV emission and extinction

NGC 1569 was observed with the Groningen University UV experiment on board the Astronomical Netherlands Satellite (ANS) in the 1550 Å to 3300 Å wavelength range in a $2.5 \times 2.5$ aperture encompassing the entire optical galaxy. A full description of the instrument and its operation was given by Wesselius et al. (1982). The resulting flux densities are given in Table I, column 2.

Unfortunately, the aperture also included the nearby bright foreground star BD+64°450 (about 55° north of the brightness center of NGC 1569). Especially at wavelengths of 2500 and 3300 Å the star may contribute significantly to the detected emission. The AGK3 gives spectral type G0 and $m_\text{eq}=10.0$, but this information is insufficient to apply a meaningful correction. At our request, P. Katgert kindly obtained a high resolution (35 Å mm$^{-1}$) spectrum of the star in the 3500–4500 Å wavelength range, using the Isaac Newton Telescope at the Roque de los Muchachos Observatory (La Palma). Comparison with the Morgan, Keenan and Kellman (1943) atlas suggests the spectral type of BD+64°450 to be G5–G8, luminosity class IV. The observed (18–22), (18–25) UV colours of NGC 1569 (see Fig. 1), uncorrected for stellar contamination, indicate a maximum galactic foreground extinction $E(B-V)=0.55$. Although somewhat higher than previous estimates $E(B-V)=0.41$, Ables, 1971; $E(B-V)=0.52$, Burstein and Heiles, 1978), it is in reasonably good agreement with those. Hence, $E(B-V)=0.55$ is also close to the maximum extinction that the foreground star BD+64°450 can suffer. Note that the location of NGC 1569 in Fig. 1 already indicates that stellar contamination at 2200 Å and 2500 Å should be minor. If it were significant, NGC 1569 would shift too far to the left and downwards, implying extremely blue intrinsic colours; at the same time, however, the implied extinction would not change by much. A minimum extinction for the star follows from the observed $B$ magnitude $(B=10.1$, corresponding to $F_B=6.0 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) and the assumption that all UV emission measured by ANS at 3300 Å is due to the star; this yields $E(B-V)=0.45$ for a G5 IV star and $E(B-V)=0.20$ for a G8 IV star (using intrinsic stellar colours by Wu et al., 1980). A more realistic lower limit can be obtained from the $U$ magnitude of NGC 1569 ($U=11.8$, corresponding to $F_U=8.0 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$; see Sect. 2.2); galaxy models by Coleman et al. (1980) show that $F_{3300}/F_U>0.4$ for all realistic cases. This implies minimum extinctions $E(B-V)=0.70$ for the G5 case and $E(B-V)=0.45$ for the G8 case. This result indicates that the latter spectral type is more probable, and that virtually all material obscuring NGC 1569 is in fact in front of the star and thus local to the Galaxy.

Columns 3, 4 and 5 of Table I list the amount of stellar contamination in the ANS measurements for three representative cases, using intrinsic stellar colours by Wu et al. (1980). From this, it is clear that stellar contamination is negligible shortwards of 2500 Å, noticeable but not major at 2500 Å and dominant at

<table>
<thead>
<tr>
<th>Wavelength $\lambda$ (Å)</th>
<th>Observed total</th>
<th>BD + 64°450 contribution</th>
<th>NGC 1569 Corrected</th>
<th>NGC 1569 Dereddened</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
</tr>
<tr>
<td>1500</td>
<td>2.29 ± 0.73</td>
<td>0.0012a</td>
<td>0.0008b</td>
<td>0.0028c</td>
</tr>
<tr>
<td>1800</td>
<td>3.53 ± 0.42</td>
<td>0.0075</td>
<td>0.0027</td>
<td>0.0092</td>
</tr>
<tr>
<td>2200</td>
<td>1.06 ± 0.16</td>
<td>0.071</td>
<td>0.019</td>
<td>0.11</td>
</tr>
<tr>
<td>2500</td>
<td>2.54 ± 0.35</td>
<td>0.29</td>
<td>0.12</td>
<td>0.34</td>
</tr>
<tr>
<td>3300</td>
<td>13.9 ± 1.16</td>
<td>13.9</td>
<td>10.1</td>
<td>14.0</td>
</tr>
</tbody>
</table>

a Assuming foreground star to be G5 IV, $E(B-V)=0.45$ mag, $V_0=7.56$.
b Same, but for G8 IV, $E(B-V)=0.55$, $V_0=7.08$.
c Same, but for G8 IV, $E(B-V)=0.45$ for all cases the distance of the star is about 145 pc; with $b=+11.2°$, this implies a $z$-distance of 29 pc.
d For $E(B-V)=0.56$.
3300 Å where at most 30% of the observed emission appears to be due to the galaxy. The implied values for the UV emission from NGC 1569 itself, with errors taking also into account the uncertainty in the correction for BD+64°450, are given in column 6 of Table 1. The corrected colours of NGC 1569 are also indicated in Fig. 1. We note that the 3300 Å flux density for NGC 1569 is rather uncertain, since it depends critically on the assumed stellar foreground emission; the 2500 Å result is much more reliable. If the extinction of NGC 1569 follows the solar neighbourhood reddening law, we obtain $E(B-V) = 0.56 \pm 0.10$; the intrinsic 18–22, 18–25 colours of NGC 1569 will then be those of a B2 star, which is the expected value for a stellar aggregate dominated by the UV light of late type O and early type B stars; the integrated light corresponds to that of a synthesised OB association of type b/c in the classification by Koornneef (1978; his Table 5). Such a situation represents either an evolved population of age about $10^7$ years or a more recent starburst deficient in early O stars.

One cannot a priori exclude the possibility that NGC 1569 suffers some internal extinction with a different reddening law, e.g. the LMC reddening law which is deficient in 2200 Å absorption. We will briefly explore this possibility. The intrinsic UV colours of an aggregate of early type stars are definitely not likely to be bluer than those of an O9 star, as this would imply a very large number of early O stars with respect to the number of late O stars and B stars. Colours corresponding to those of an O9 star already represent a synthesised OB association of type a (Koornneef, 1978; his Table 5) enriched in early O stars. From Fig. 1 we find for that case $E(B-V) = 0.34$ (LMC reddening law in addition to $E(B-V) = 0.50$ (solar neighbourhood law). This would make NGC 1569 intrinsically very bright; the integrated luminosity of its early type stars alone would be of order $10^8$–$10^9 L_\odot$; it also would lead to a predicted thermal radio flux density $S_{\nu,\text{HII}} > 1 \text{ Jy}$ which is much more than the total flux density observed for NGC 1569 (see Israel and De Bruyn, 1988).

We conclude that $E(B-V) = 0.56 \pm 0.10$ by mostly galactic foreground dust is the most likely situation, and that the UV observations represent a stellar population resulting from a burst of star formation of order $10^7$ years ago consistent with Sandage’s (1956) version of Salpeter’s (1955) initial luminosity function. UV flux densities corrected for extinction are given in Table 1, column 7.

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Fig. 1. UV colour-colour diagram (1800–2200 Å; 1800–2500 Å) showing the position of NGC 1569 as observed and as corrected for the flux contribution of the foreground star BD+64°450 (see text Sect. 3.1). Also indicated are main-sequence stellar colours and solar neighbourhood and LMC reddening lines. By way of comparison, observed colours of some extragalactic HII regions are also indicated, taken from Israel et al. (1982, 1986).
3.2. Optical emission and distance

From Ables (1971) and De Vaucouleurs et al. (1976) we find that the optical brightness of NGC 1569 is best described by $U = 11.80$, $B = 11.96$ and $V = 11.17$, so that $(U - B) = -0.16$ and $(B - V) = +0.79$. These magnitudes may be converted to flux-densities by taking the $UBV$ calibration given e.g. by Allen (1973, p. 202). We have included these values in Table 2 and Fig. 2. Taking $E(B - V) = 0.56$ from Sect. 3.1 and applying a standard solar neighbourhood reddening law, we arrive at dereddened magnitudes $U_0 = 9.02$, $B_0 = 9.64$ and $V_0 = 9.41$ for the integrated light of NGC 1569, yielding very blue intrinsic colours $(U - B)_0 = -0.62$ and $(B - V)_0 = +0.23$. Again, these area-integrated colours correspond to those of an early B star. Adopting an apparent distance modulus $(m - M)_0 = 29.0 \pm 0.5$ mag (cf. Ables, 1971; Arp and Sandage, 1985) and correcting for extinction $E(B - V) = 0.56 \pm 0.10$, we find a true distance modulus $(m - M)_0 = 26.7 \pm 0.6$, hence a distance $D = 2.2 \pm 0.6$ Mpc and an absolute magnitude $M_B = -17.1 \pm 0.6$. At this distance, the size of NGC 1569 down to a blue surface brightness of 25 mag arcsec$^{-2}$ (De Vaucouleurs et al., 1976) is 1.85 \pm 0.95 kpc.

Kennicutt and Kent (1983) have measured the H$\alpha + [\text{N} \text{II}]$ emission from NGC 1569 in a 3′ aperture, encompassing the entire visual image of the galaxy. They find an equivalent width of 149 \pm 15 Å and a ratio $[\text{N} \text{II}]/\text{H} \alpha = 0.11$. This translates into a flux $f(\text{H} \alpha) = 2.26 \pm 0.23 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. If the observed H$\alpha$ emission suffers $E(B - V) = 0.56 \pm 0.10$ (Sect. 3.1), the extinction-corrected emission is $f_0(\text{H} \alpha) = 8.2 \pm 1.9 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$. In turn, this corresponds to a thermal flux density at radio wavelengths of $S_{\text{GHz}} = 80 \pm 19$ mJy. Note that about 55% of this predicted flux density was found to be present in the brightest eleven H$\text{II}$ region complexes by Israel (1980). For a further discussion of the radio continuum spectrum and nonthermal emission of NGC 1569 we refer to Israel and De Bruyn (1988).

### Table 2. Optical emission from NGC 1569

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>Observed $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$</th>
<th>Dereddened$^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>3650 (U)</td>
<td>0.81</td>
<td>10.5</td>
</tr>
<tr>
<td>4400 (B)</td>
<td>1.09</td>
<td>9.2</td>
</tr>
<tr>
<td>5500 (V)</td>
<td>1.29</td>
<td>6.6</td>
</tr>
</tbody>
</table>

$^*$ Adopted $E(B - V) = 0.56$

3.3. Infrared properties

The IRAS point source catalog (PSC) includes a clear detection of NGC 1569. Colour-corrected flux densities are given in Table 3. The FIR flux parameter given in the PSC $L_{\text{PSC}} = 2.19 \times 10^{-12}$ W m$^{-2}$ corresponds to a luminosity $L = 3.3 \times 10^8 L_\odot$ at a distance of 2.2 Mpc. However, observations with the IRAS Chopped Photometer Channel (F. Sloff, unpublished) show that the galaxy is slightly extended at 50 and 100 μm with a size of 1′. Applying this to the PSC flux densities at 60 and 100 microns raises the luminosity to $L = 4.5 \pm 0.6 \times 10^8 L_\odot$ (for $D = 2.2$ Mpc), which should be a fair represen-
Table 3. Infrared emission from NGC 1569

<table>
<thead>
<tr>
<th>Wavelength (micron)</th>
<th>Observed flux-density* (Jansky)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>0.54 ± 0.07^b</td>
<td>IRTF Map</td>
</tr>
<tr>
<td>12</td>
<td>0.05 ± 0.03</td>
<td>IRAS PSC</td>
</tr>
<tr>
<td>14</td>
<td>0.9 ± 0.2</td>
<td>IRAS LRS</td>
</tr>
<tr>
<td>16</td>
<td>1.7 ± 0.3</td>
<td>IRAS LRS</td>
</tr>
<tr>
<td>19</td>
<td>3.5 ± 0.5</td>
<td>IRAS LRS</td>
</tr>
<tr>
<td>25</td>
<td>8.4 ± 0.5</td>
<td>IRAS PSC</td>
</tr>
<tr>
<td>25</td>
<td>8.4 ± 0.5</td>
<td>IRAS PSC</td>
</tr>
<tr>
<td>50</td>
<td>83:</td>
<td>IRAS CPC</td>
</tr>
<tr>
<td>60</td>
<td>69 ± 7</td>
<td>IRAS PSC</td>
</tr>
<tr>
<td>100</td>
<td>55 ± 11^c</td>
<td>IRAS PSC</td>
</tr>
<tr>
<td>100</td>
<td>79:</td>
<td>IRAS CPC</td>
</tr>
</tbody>
</table>

^a Colour-corrected.

Dereddened with $E(B-V) = 0.56$.

^c Corrected for finite source extent 1':4

The total luminosity between 1 and 500 $\mu$m then will be $7 \pm 1 \times 10^8 L_\odot$ (see Appendix B, IRAS, 1985). Table 3 lists the adopted IRAS flux densities; the values at 12 and 25 $\mu$m are as given in the PSC, since the extent of the source at these wavelengths is unknown, but unlikely to be large compared to the beam as NGC 1569 does not appear in the IRAS Small Scale Structure (SSS) Catalog. The far-infrared spectrum is graphically shown in Figure 3, which also contains flux densities at 50 and 100 $\mu$m obtained from IRAS CPC maps (F. Solf, unpublished). We give these values little weight, however, as the CPC calibration is relatively uncertain. Figure 3 also shows some flux density determinations between 12 and 25 $\mu$m, obtained from the IRAS LRS spectrum; the spectrum is too noisy to show individual spectral features, but yields continuum flux densities in good agreement with the broadband 12 and 25 $\mu$m observations. The IRAS colours place NGC 1569 to the extreme left of other galaxies discussed by Helou (1986), indicating the presence of a radiation field several hundred times that of the solar neighbourhood as well as the absence of cool 'cirrus'.

We have also mapped NGC 1569 in an 11'' aperture with full sampling (6'') at 2.2 $\mu$m using the IRTF. Standard stars were SJ

![Fig. 3. Infrared spectrum of NGC 1569, including IRAS survey, CPC and LRS data, as well as the integrated K-band flux density obtained with the IRTF. For comparison purposes, the KAO far-infrared spectrum of the central 50'' obtained by Rickard and Harvey (1984) is also shown (see text Sect. 3.3)](image-url)
9512 with $K = 7.18$ and SJ 9531 with $K = 7.31$ (Elias, 1982). Measured atmospheric attenuation was 0.17 mag per airmass at 2.2 $\mu$m. Unfortunately, there was insufficient time to completely map the galaxy, although most of it was covered. The result is shown in Fig. 4. Integration of this map yielded a total flux density of $450 \pm 45$ mJy (corrected for atmospheric attenuation, and interstellar extinction $A_{2.2\mu m} = 0.17$ mag); in Table 3 we list a somewhat higher value resulting from extrapolating the infrared intensity distribution beyond mapping boundaries, using the optical image as a guide. The integrated, extinction-corrected flux corresponds to $K = 7.66$. The IRAS spectrum shows that hot dust at most makes a negligible contribution to the $K$ band emission. Thus, the $K$ magnitude represents the stellar component of NGC 1569. The resulting colour ($V-K)_0 = 1.7 \pm 0.2$ corresponds to that of a G5V star (Koornneef, 1983).

4. Global parameters of NGC 1569

4.1. Luminosities

In the following, we base ourselves on a distance of 2.2 Mpc for NGC 1569 (see Sect. 3.2). Integration and extrapolation of the extinction-corrected UV spectrum shortwards of 3000 $\AA$ yields a total luminosity of $4.4 \pm 1.0 \times 10^9 L_\odot$. Integration and extrapolation of the extinction-corrected optical spectrum longwards of 3000 $\AA$ yields a total luminosity of $7.4 \pm 1.9 \times 10^9 L_\odot$. Hence the total stellar luminosity of NGC 1569 is $1.2 \pm 0.3 \times 10^9 L_\odot$.

In Sect. 3.3 we found a total far-infrared luminosity $L_{IR} = 7 \pm 1 \times 10^8 L_\odot$; integration and extrapolation of the observed far-infrared spectrum yields a very similar result. Another way of estimating the total far-infrared luminosity is by scaling the results for the central 50" of NGC 1569 between 40 and 160 $\mu$m obtained by Rickard and Harvey (1984) and also shown in Fig. 3. The temperature obtained by them is very close to the one implied by the IRAS observations; between 50 and 100 $\mu$m their flux densities are about a third of the ones detected by IRAS. Adapting their result to a distance of 2.2 Mpc, and scaling by a factor of three, we obtain $L_{IR} = 5.6 \times 10^8 L_\odot$, again very close to the value found in Sect. 3.3.

We conclude that the stellar luminosity in the visual range is about one and a half times that in the UV range, and that the total luminosity reradiated in the far-infrared is about 60% of the total stellar luminosity.

4.2. Masses

Again we reduce all values to a distance of 2.2 Mpc. Roberts' (1968) H I mass then becomes $M(H I) = 1.3 \times 10^8 M_\odot$, while Reakes' (1979) results imply $M(H I) = 0.8 \times 10^8 M_\odot$; we adopt $M(H I) = 1.1 \pm 0.2 \times 10^8 M_\odot$. If we take into account the presence of helium, the total atomic gas mass is $M(H I + He) = 1.5 \pm 0.3 \times 10^8 M_\odot$. The total mass of NGC 1569 determined by Reakes (1979) becomes $M_T = 3.3 \times 10^8 M_\odot$. Hence, we have $M/L = 0.3 \pm 0.1 M_\odot/L_\odot$ and $M(H I + He)/M_T = 0.46 \pm 0.09$; a considerable fraction of the total mass resides in the neutral atomic gas. Dust masses were estimated by Hunter et al. (1986) from the IRAS measurements. For a distance of 2.2 Mpc, and a 60 $\mu$m flux density of 69 Jy their results become $M_d = 6 \times 10^4 M_\odot$ for the silicate model and $3 \times 10^4 M_\odot$ for the graphite model. Hence, as noted by Hunter et al. (1986), the dust mass is only a small fraction of the total mass ($M_d/M_T = 1.3 \pm 0.4 \times 10^{-4}$) and also of the neutral hydrogen gas mass ($M_d/M(H I) = 3.6 \pm 1.2 \times 10^{-4}$).

4.3. Dust abundance and metallicity

The dust-to-gas ratio in NGC 1569 thus found is a factor of 20 lower than the canonical value $6.7 \times 10^{-3}$ found in the solar neighbourhood (e.g. Osterbrock, 1974, p. 181); it is comparable to

![Fig. 4. K-band map of NGC 1569, obtained with the IRTF. Dashed contours indicate extrapolation of observed map using the optical image as guide. Peak emission in NGC 1569 coincides with 'stellar' object A. Bright point source at top is the partially mapped foreground star BD 64°450. Contours are drawn at 2.5, 5.0, 7.5, and 10 to 45 mJy per beam in intervals of 5 mJy per beam. The IRTF beam is indicated.](image-url)
the dust-to-gas ratio inferred for the Small Magellanic Cloud (Koornneef, 1984). This notion finds support in the infrared spectrum of the central 50° of NGC 1569 by Rickard and Harvey (1984) which extends to 160 μm and indicates a lack of relatively cool dust (which IRAS could not have detected), and in our result that relatively little extinction should be associated with NGC 1569 itself (Sect. 3.1). The high colour temperatures observed in the far-infrared are consistent with the presence of small amounts of dust heated to relatively high temperatures by an intense stellar radiation field (see also Hunter et al., 1986). The severe dust depletion implied by the far-infrared observations should be compared to the low metallicity inferred for the ionized gas in NGC 1569: [O]/[H] = 1.8 × 10^{-4} (Hunter et al., 1982), which is about half the Orion abundance, and roughly in between the abundances found for the LMC and the SMC (Dufour et al., 1982). The same applies to the [Ne]/[H] abundance ratio. If all abundances scale analogously to those in the LMC and SMC, we predict a carbon abundance only 15% of the Orion carbon abundance (cf. Dufour et al., 1982).

This has some relevance to the weakness of CO emission observed towards NGC 1569 (Young et al., 1984). For the LMC and the SMC, Israel et al. (1986) argue that in those galaxies CO is weak because of photo-dissociation of CO by a strong UV radiation field coupled with weak dust shielding and relatively low CO abundance (primarily as a consequence of a low carbon abundance). Assuming a CO to H₂ conversion essentially the same as that in the solar neighbourhood, Young et al. (1984) find M(H₂) = 7 × 10^8 M☉ for D = 4.7 Mpc for the central 50° in NGC 1569. Reducing this to D = 2.2 Mpc, multiplying by a factor of three (in analogy to the far-infrared emission ratio between the whole galaxy and the central 50°) and assuming a CO emissivity decrease by a factor of four relative to strongly self-shielding H₂ (as in the SMC, Israel et al., 1986), we arrive at an estimate for the total molecular hydrogen mass M(H₂) = 2 × 10^7 M☉ or M(H₂)/M(H↓) = 0.15 for the galaxy as a whole. However, with the CO emissivity correction factor of four, we would have in the central region a mass ratio M(H₂)/M(H↓) = 2.5, making NGC 1569 less exceptional than Young et al. (1984) argue. We conclude that NGC 1569 in its low metallicity and low dust content resembles the Magellanic Clouds, that this resemblance extends to its CO content, but that its H₂ content relative to its H↓ content may well be normal compared to e.g. the Galaxy.

4.4. Star formation

The blue colours, high dust temperatures and strong H₂ emission of NGC 1569 all indicate that the galaxy is presently showing the effects of a strong burst of star formation. Recent massive star formation rates can be estimated from e.g. the H₂ observations by Kennicutt and Kent (1983) summarized in Sect. 3.2. Their extinction-corrected H₂ emission corresponds for T_{exc} = 10^4 K to a Lyman continuum photon production of N_{H↓} = 3.5 ± 1.1 × 10^{52} photons s^{-1}, which by way of illustration corresponds to the output of 2000 06 stars (Panagia, 1973). If we assume that stars of spectral type O6 and earlier no longer significantly contribute to N_{H↓}, a Salpeter (1955)/Sandage (1956) type IMF/LIF in the range O7 to K5 yields a total mass of stars formed in the burst M_{star} = 2 ± 1.10^8 M☉. For a burst duration of 2.1 10^7 yr, a star formation rate dM/dt = 0.1 M☉ yr^{-1} follows. This is a lower limit, however, because (a) Lyman continuum photons may escape from the galaxy, and (b) at least some of the ionized regions may suffer from extinction inside NGC 1569. Hence, the star formation rate implied by the H₂ emission of NGC 1569 is taken to be dM/dt = 0.2 ± 0.1 M☉ yr^{-1}. In a similar way, we obtain an independent estimate dM/dt = 0.3 ± 0.1 M☉ yr^{-1} from the intrinsic UV emission from NGC 1569.

Yet another way of finding the characteristics of the recent star formation burst in NGC 1569 is by applying the theoretical models calculated by Larson and Tinsley (1978) and Struck-Marcell and Tinsley (1978) to the intrinsic U – B, B – V and V – K colours of the galaxy. The galaxy is far too blue to fit any of the continuous star formation models, but agrees well with the single burst models. Taking into account metallicity effects, and assuming a burst duration of 2.10^7 years we find that the observed colours are reproduced by a burst with strength h = 0.03 – 0.05 (ratio by mass of newly formed stars over all stars in NGC 1569) which took place 1 – 2 10^7 years ago. This result is in excellent agreement with the finding by Israel and De Bruyn (1988) that relativistic electron injection rates, hence supernova rates, sharply decreased 5 · 10^7 years ago. Since the total stellar mass of NGC 1569 does not exceed 2 · 10^8 M☉ (cf. Sect. 4.2), star formation rates during the burst were dM/dt = 0.3 ± 0.5 M☉ yr^{-1}. We adopt a burst star formation rate dM/dt = 0.3 ± 0.1 M☉ yr^{-1} as the most likely value. This value is three times the one found by Hunter et al. (1982) and about a quarter of the value found by Israel (1980) after reducing both to a distance of 2.2 Mpc. Obviously, if the burst formed only massive stars, the above values have to be reduced. Note also that present (postburst) star formation rates should be much lower.

Since most of the interstellar gas mass resides in the neutral atomic gas, the supply still available for further star formation would be completely exhausted in about 5 · 10^8 years at burst star formation rates. Taking into account the structure of NGC 1569, depletion times in the central parts would be up to an order of magnitude shorter. If NGC 1569 has an age of 1.5 · 10^10 years, its time-averaged star formation rate must be dM/dt = 0.01 – 0.02 M☉ yr^{-1}, which explains its low metallicity, and also suggests that its gas-supply allows another 10^10 years of star formation.

If the recent burst was characteristic for the star formation history of NGC 1569, some 25 bursts must have occurred in the past at intervals of on average 6 · 10^8 yr. With a burst duration of 2 · 10^7 yr and a transition phase of 1 · 10^7 yr (cf. Israel and De Bruyn, 1988) the galaxy then has been in an active phase about 5% of its lifetime. It was characterized by very blue colours (e.g. \(U - B\)_0 < -0.2) for about 10%–20% of its lifetime (cf. Struck-Marcell and Tinsley, 1978; Larson and Tinsley, 1978). Extrapolating these values to other galaxies, we would expect that about a third of all blue compact galaxies has detectable radio continuum emission. This estimate is in good agreement with the results from a 4.75 GHz radio continuum survey carried out by Klein (1986) who detected about 40% of a sample of 45 blue compact dwarf galaxies. If indeed NGC 1569 is typical, about a quarter of all blue dwarf galaxies detected in the radio continuum (i.e. of order 10% of all blue dwarf galaxies) then is expected to have a high-frequency spectral turnover in the 1–10 GHz range (cf. Israel and De Bruyn, 1988). However, this will only be apparent for galaxies with well-determined flux-densities in the range 0.5–20 GHz; at present this is only a very small number.

It should finally be noted that the results on NGC 1569 suggest that most (dwarf) galaxies considered to be star-burst galaxies on the basis of very blue optical colours are in reality
post-starburst galaxies. If the duration of the starburst itself is short (i.e. $\lesssim 10^7$ years), chances of finding a galaxy in the postburst phase are much larger than finding one in the burst-phase. This is especially the case if the newly formed stars are initially surrounded by dust clouds. As radio emission from such a galaxy predominantly originates in very massive stars (H II regions, supernova remnants) while the blue light represents a larger range of masses, the most recent starbursts should be characterized by the highest radio-to-blue luminosities.

5. Conclusions

1. The blue irregular dwarf galaxy NGC 1569 suffers a (Galactic foreground extinction) $E(B - V) = 0.56 \pm 0.10$. It is located at a distance of $2.2 \pm 0.6$ Mpc.

2. At this distance, its stars have an integrated luminosity $L = 1.2 \pm 0.3 \times 10^3 L_\odot$ and emit the larger fraction of this in the visual range; about 60% of the total stellar luminosity is re-emitted in the far-infrared.

3. The optical size of the galaxy is about $2 \times 1$ kpc; its total mass is $M_T = 3.3 \times 10^8 M_\odot$. Almost half of the total mass resides in neutral atomic gas.

4. The dust-to-gas ratio is one twentieth of that in the solar neighbourhood, and comparable to that of the SMC. It is in line with the observed low metallicity of the galaxy.

5. Although the amount of molecular hydrogen is poorly known, this could in principle be a large fraction of interstellar medium in the central parts of NGC 1569. It is not expected to be a major contributor to the total interstellar mass.

6. Both UV and optical photometry show the galaxy to contain a sizeable OB star population, deficient in very early O stars.

7. This is interpreted as the aftermath of a strong burst of star formation which occurred $1 - 2 \times 10^7$ years ago and had a strength between 3% and 5%. If the burst duration was $2 \times 10^7$ years, burst star formation rates were $dm/dt = 0.3 \pm 0.1 M_\odot$ yr$^{-1}$.

8. If the recent burst was characteristic for the star formation history of NGC 1569, the mean time between bursts in the past was of order $6 \times 10^8$ years and the galaxy is in an active star-forming phase about 5% of the time.

9. If in addition NGC 1569 is typical for blue compact dwarf galaxies in general, about a third of all blue dwarfs should be a significant source of radio emission, and about a quarter of those should have a high-frequency radio spectral turnover between 1 and 10 GHz.

10. Most (dwarf) galaxies labeled as starburst galaxies will in fact be post-starburst galaxies, which is reasonable in view of the suspected short duration of bursts of star formation. The most recent bursts will be characterized by the highest radio to blue luminosity ratios.

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Note added in proof: After submission of this paper, my attention was drawn to a paper by J.S. Gallagher, D.A. Hunter and A.V. Tutukov (1984, Astrophys. J. 284, 544) in which they also derive a high recent star formation rate for NGC 1569 and interpret this as indicating that NGC 1569 is either a young galaxy, or has an IMF different from the Salpeter function. However, reducing the distance to the value of 2.2 $M_\odot$ used here alleviates the need for such extreme conclusions.