A SUPERGIANT SUPERNOVA-BLOWN BUBBLE IN THE SPIRAL GALAXY NGC 1620

J. Patricia Vader and Brian Chaboyer

ABSTRACT

We present UBR and Hα imaging of NGC 1620, a highly inclined spiral galaxy that contains a large scale, arc-like feature of radius 3 kpc in its outer disk at a distance of ∼11 kpc from the center. What is unusual about this arc-like feature is its stellar nature and the presence of a luminous star cluster at its center. The arc is fragmented into HII region complexes and OB star clusters and shows two kinks in optical continuum light. It spans an angle of 220° on our U image and a full, though fragmented, circle on an unsharp masked R image. It is centered on a young star cluster that is the most luminous clump in blue optical continuum light besides the nucleus of the galaxy. This central star cluster has UBR colors and a surface brightness similar to those of other HII regions, but is a relatively weak Hα emitter. It consists of at least three unresolved condensations in optical continuum light. Its location at the center of the arc and its prominence within the galaxy suggests that it has been the site of several generations of supernova explosions that swept up the surrounding gas into a supershell. When it attained a radius of 0.5 – 1 kpc, this shell became gravitationally unstable and formed the stars which now delineate the arc. The constraints imposed by the survival of the expanding arc against random stellar motions and the age of the stars in the arc yield a required energy input by a minimum of 400 and a maximum of 6500 supernovae. In this scenario the asymmetry in surface brightness of the arc reflects the radial gradient of the gas density in the disk of NGC 1620, while the kinks reflect inhomogeneities in the original gas distribution with respect to the central star cluster. The supernova superbubble formed at least $5 \times 10^7$ yr ago so that, unless supernova explosions continued after the onset of star formation in the expanding shell, the bubble interior has cooled and the corresponding hole in the HI distribution no longer exists. An unsharp masked image reveals the presence of a central bar in NGC 1620 which we therefore reclassify as an SBbc galaxy.

Subject headings: galaxies: Individual, NGC 1620 – galaxies: Star Clusters – galaxies: Spiral – ISM: Bubbles – ISM: General – HII regions

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1. Introduction

A shell-like feature with a radius of 3 kpc and centered on a bright condensation was discovered in the disk of the spiral galaxy NGC 1620 on a blue continuum image (Chaboyer and Vader 1991; hereafter CV91). The high degree of apparent circular symmetry of this feature, which is embedded in a highly inclined galactic disk, suggested that it is a nearly spherically symmetric shell. CV91 interpreted it as a supergiant supernova-blown bubble that formed \( \sim 10^8 \) years ago as the result of at least 150 supernova explosions. In this scenario the shell of expanding gas became gravitationally unstable and formed stars which should now be visible predominantly as stars of type later than B3. We report here follow-up observations to test this hypothesis. We have obtained UBR and H\( \alpha \) CCD imaging, as well as low S/N optical spectra of the star cluster at the center of the arc and of the nucleus of NGC 1620.

NGC 1620 is a highly inclined Sbc galaxy of absolute blue magnitude \(-21.0\), with normal optical and far-infrared properties (Rubin, Ford, & Thonnard 1978; CV91) and a typical neutral hydrogen content (Shostak 1978). We adopt a distance of 45.7 Mpc based on the recession velocity found by Rubin et al. (1978) and \( H_0 = 75 \) km s\(^{-1}\) Mpc\(^{-1}\). This yields a linear scale of 222 pc per arcsecond. The observations and data reduction are presented in Section 2. The analysis and interpretation of the data are given in Sections 3 and 4, respectively. Conclusions are summarized in Section 5.

2. Observations and Data Reduction

2.1. Broad Band Optical Imaging

CCD imaging of NGC 1620 was obtained with the CTIO 0.9m telescope in November 1990. The detector was a 800 \times 800 pixel T1 Chip, binned to 2 \times 2 pixels, yielding 400 \times 400 pixel images with a scale of 0.494''/pixel. The log of the observations is given in Table 1. On all U, B and R frames bad columns run East-West across the southern half of the galaxy. The U and B frames are shown in Figures 1 and 2, respectively. All nights were photometric. Ten to sixteen standard stars taken from Landolt (1983, 1992) and Graham (1982) were observed per night. The data reduction was done with the IRAF software package. The images have been flat-fielded and debiased in the standard way. The instrumental magnitudes are corrected for atmospheric extinction and converted to UBR magnitudes on the Cousins system. The transformation equations are given in Table 1. The extinction coefficients used in B and R are taken from Landolt (1983). From observations of sixteen standard stars we derive an extinction coefficient in U of 0.87 mag (unit airmass)\(^{-1}\), which is the value used here rather than that given by Landolt (1983).

The photometry errors consist of three components: the systematic and rms errors of the zero-point in the photometric transformations (the ‘external’ error), the random error in aperture measurement and the error in the adopted mean sky value (the ‘internal’ errors). The sum of the latter two errors defines the relative errors. We have calculated the sum of the latter two errors in intensity, i.e., ADU counts, as \( \Delta I = (N_{tot}/g/m + (\delta n_{sky} A)^2) \) with \( N_{tot} \) the total number of counts as measured within aperture \( A \), \( g \) the gain (1.89 e-/ADU), \( n_{sky} \) the mean sky counts per pixel and \( \delta \) the fractional error in the mean sky value. This gives a signal-to-noise ratio of \( \Delta I/(N_{tot} - A) \). The read noise is low (5.89 e-) and represents a negligible contribution. The uncertainty in the mean sky value is 0.3% in B and R and 0.4% in U. For areas with surface brightness much below sky the random error in magnitude can be approximated by \( N_{sky}^1/N_{object} \), while a relative error \( \delta \) in the mean sky yields a magnitude error of \( \delta N_{sky}/N_{object} \).

2.2. H\( \alpha \) imaging

Two filters were selected for H\( \alpha \) imaging: a filter of central wavelength 6653 Å and a FWHM of 76 Å, centered on the H\( \alpha \) emission line at the redshift of NGC 1620, and an adjacent filter of central wavelength 6529 Å and a FWHM of 75 Å which was used to measure the continuum emission in the vicinity of the H\( \alpha \) line (Table 1). The line + continuum image suffered from poor tracking, showing east-west elongated star images with an ellipticity of around 0.1. The line image was smoothed with an elliptical gaussian to match the PSF of the poorer-seeing, distorted line + continuum image to form the final line image. Four standards from Stone and Baldwin (1983) were observed with both filters. The transformation equations are given in Table 1, with \( m_{\nu} \) the monochromatic magnitude at 6653 and 6529 Å and the extinction coefficient taken from Stone and Baldwin (1983). We used these results to scale and subtract the ‘continuum’ frame at 6529 Å from the ‘line + continuum’ frame at 6653 Å (of similar airmass \( X \)) according to

\[
I(H\alpha) = I_c - \text{dex} \left[-0.4(C_c - C_{lc})/I_c\right],
\]

with \( I \) the intensities, \( C \) the zero-points in the transformation equations (Table 1), and subscripts \( c \) and \( lc \) referring to the ‘continuum’ and ‘line + continuum’ frames, respectively. The resulting H\( \alpha \) image is
shown in Figure 3a. The stars on the original frames have been fully removed as expected. The galaxy was offset with respect to the center of the chip to capture the totality of the arc-like feature which extends well beyond the disk of NGC 1620. It is positioned well away from the bad columns of the CCD chip. Monochromatic magnitudes at 6653 Å are derived from photometry on this image using the corresponding equation in Table 1. These are converted to monochromatic fluxes following the prescription of Baldwin and Stone (1983) and multiplied by the effective filter width, ∆λ = 68 Å, to obtain Hα emission line fluxes according to \( F(\text{H}α) = f_{\nu \text{c}} \Delta \lambda / \lambda^2 \). The photometry errors in the mean 'sky' value is about 1%.

2.3. Spectroscopy

Spectra of the nucleus of NGC 1620 and the central star cluster within the arc were obtained with the 2D Frutti detector at the CTIO 1m telescope on 24 November 1990. The instrumental setup corresponded to a slit width of 2" and an effective resolution of 16.5Å FWHM, yielding a nominal accuracy in velocity centroid of ∼ 100 km s\(^{-1}\). Total exposure times were 1880s and 4200s for the nucleus and the star cluster, respectively. Observations of two standard stars from Stone and Baldwin (1983) were used to flux calibrate the spectra. The flat-fielded and calibrated spectra are shown in Figure 4. The 4000 Å break, the H and K lines in absorption and the star cluster, respectively. Observations of exposure times were 1880s and 4200s for the nucleus and an effective resolution of 11.1 kpc if we assume it to be located in the mid-plane of the galactic disk.

A sharply delineated, very straight dust lane, with a width of about 1.8", runs along the South-East side of the disk of the galaxy, at the edge of the region dominated by spiral structure, in a direction slightly tilted with respect to the major axis of the galaxy. The dust lane is visible on our U, B and R frames but more prominently so on the B frame (Fig. 1) and the unsharp masked R frame discussed below (Fig. 10). From the shape of the spiral pattern and the direction of rotation (Rubin et al. 1978), we infer that

### TABLE 1: CCD Imaging Observations

<table>
<thead>
<tr>
<th>Filter</th>
<th>Date Nov 1990</th>
<th>Seeing FWHM</th>
<th>Exposure Time (s)</th>
<th>Transformation Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>18</td>
<td>1.5&quot;</td>
<td>2700</td>
<td>( B = 1.008(b - 0.283X) - 0.37 \pm 0.04 )</td>
</tr>
<tr>
<td>R</td>
<td>18</td>
<td>1.3&quot;</td>
<td>1800</td>
<td>( R = 0.987(r - 0.130X) - 0.05 \pm 0.03 )</td>
</tr>
<tr>
<td>U</td>
<td>21</td>
<td>1.5&quot;</td>
<td>3600</td>
<td>( U = u - 0.87X + 0.48(U - B) - 1.22 \pm 0.03 )</td>
</tr>
<tr>
<td>6653 Å, lc</td>
<td>17</td>
<td>1.7&quot;</td>
<td>3600</td>
<td>( m_\nu = m_{\text{inst}} - 0.09X - 6.224 \pm 0.062 )</td>
</tr>
<tr>
<td>6529 Å, c</td>
<td>17</td>
<td>1.7&quot;</td>
<td>3600</td>
<td>( m_\nu = m_{\text{inst}} - 0.09X - 6.518 \pm 0.049 )</td>
</tr>
</tbody>
</table>

\( a, b, r \) and \( m_{\text{inst}} \) are the instrumental magnitudes corrected to 1 second exposures; \( X \) is the airmass.

3. Data Analysis

The almost circular arc that stands out on the CCD B-band image (of seeing 3.3" FWHM) shown in CV91 appears as a less regular and more clumpy feature on the deeper, better seeing (1.5" FWHM) B image shown here in Figure 1. The arc and the bright condensation at its center are most prominent on our U frame (Fig. 2), indicating that it consists predominantly of OB stars. It spans ~ 220° in the disk region of the galaxy, shows two noticeable kinks, and is broken up in distinct condensations. Our Hα image is less deep than our U image, which is presumably the reason that many of the U-bright condensations in Figure 2 are not visible in Hα. On the B (Fig. 1) and R (not shown) images which sample somewhat older stellar populations the arc is a more diffuse feature. The central star cluster is irregular in shape and seems to have at least three components. This is most evident on our R image which has the best seeing. A contour plot of the central 9.4" × 9.4" region of the clump (Fig. 5) shows a dominant condensation, a fainter one to the S-W and a more diffuse and redder (see U-R color image in Fig. 6) extension to the W-N. The cluster lies South-East from the major axis of NGC 1620, with an actual galactocentric distance of 11.1 kpc if we assume it to be located in the mid-plane of the galactic disk.
the S-E side of the disk is the near side as would also be expected from the location of the dust lane. The fact that the velocity of the star cluster is larger than that of the nucleus (by 0.7σ, Sect. 2.3) is consistent with the fact that the South-West side of the disk is receding from us with respect to the nucleus due to differential rotation. The overall continuum light distribution of the galaxy shows no other perturbations or large scale asymmetries.

3.1. The brightest Hα knots

Bright knots stand out on the Hα line flux image of the southern two thirds of N1620 shown in Figure 3a. We have marked the most prominent Hα knots on the overlay for this image shown in Figure 3b (this figure can also be used as an overlay for Figs. 1, 2, 6 and 10). We can roughly define a circular ring of radius 14′′ outlined by seven distinct Hα-emitting regions, labeled from 1 to 7 on Figure 3b, and centered on the position of the star cluster as seen in continuum light. The position of the star cluster has been chosen as the geometrical center of its extended light distribution, which lies 3 pixels East of the region of peak intensity in continuum light. We identify six other bright Hα condensations visible on Figure 3a, labeled A to G in Figure 3b, all of which are located in the spiral arms of NGC 1620 as outlined by the broad band images. Regions 7, 1, 2, 3 and 4 are seen to be connected by diffuse Hα emission. Region 6, located near the eastern edge of the disk, appears isolated and surrounded by diffuse emission. Weak Hα emission can be seen near the center of the area enclosed by the 14′′ radius ring. We can distinguish three low surface brightness peaks — labeled a, b and c — that are aligned in a South-North direction. The peaks are clearly apparent in an Hα surface brightness profile along a South-North cut through the center of the ring. The center of the 14′′ radius ring is seen to lie in between peaks a and b. All the Hα knots also stand out on our U frame, though regions 6 and F are relatively weak. Region 1 appears isolated. Regions 2 through 5 are part of the continuous though clumpy arc of enhanced emission. Region 2 is the last bright knot at the S-W end of the arc, and region 1 is part of a small loop East of the arc and connecting regions 2 and 3.

We determined position offsets between the Hα image and the UBR images using knot D, which is present on all images, and obtained broadband photometry of the Hα knots. The radial extent (chosen to include about 90% of the flux before overlap with a neighboring region), Hα luminosities, optical colors and positions with respect to the nucleus of the galaxy of the Hα knots are given in Table 2. Magnitudes and fluxes were corrected for a foreground extinction of $A_B = 0.22$ for NGC 1620, using the relations $E(B - V) : A_B : E(U - B) : E(B - R) : A(Hα) = 1 : 4.1 : 0.78 : 1.78 : 2.3$. The relative or ‘internal’ errors of the magnitudes given in Table 2 are $< 0.02$ mag in R, $< 0.01$ in B and in the range 0.01 to 0.05 in U, so that the absolute errors tend to be dominated by the ‘external’ errors due to the photometric transformations (cf. Sect. 2.1). The net errors in the Hα luminosities given in Table 2 are less than 10% for all objects. Figure 7 shows the average Hα surface brightness of the individual knots against their linear extent and a radial profile of differential Hα surface brightness of the central star cluster. It is immediately obvious that the central star cluster is a much weaker Hα emitter than any of the knots. The plateau in the profile at $r = 10 - 15''$ is of course due to the arc.

A few condensations have Hα luminosities in excess of $3 \times 10^{39} \text{erg s}^{-1}$, which would qualify them as giant HII regions according to Kennicutt and Chu (1988). However, the irregular shapes, large linear radii (500 to 900 pc) and low surface brightness (e.g., compare the values in Figure 7 to the limiting outer contour surface brightness of 0.6 $L_\odot \text{pc}^{-2}$ adopted for HII regions by Hunter and Gallagher (1985)) of the Hα-emitting regions as well as their resolution into clumps on our U image indicate that they are complexes of HII regions rather than individual giant HII regions. In this case the luminosities and sizes are overestimated. On the other hand, if internal extinction is important the luminosities are underestimated. We derive below an upper limit to the internal extinction from a UBR color-color diagram and then consider resolution effects by examining an Hα luminosity versus linear size diagram.

3.2. UBR colors and internal extinction

In a UBR color-color diagram (Fig. 8) the Hα complexes occupy a narrow strip, with apparent B-R colors typical of F5 to G8 type main-sequence stars and U-B colors typical of B type main-sequence stars. An internal reddening of $E(B - V) = 0.75$ would be required for the Hα knots to have true colors typical of OB type stars. This is truly an upper limit, close to the maximum value inferred for better resolved extragalactic HII regions (Kennicut 1984) and also much larger than the typical internal extinction of $E(B - V) = 0.16$ expected for a galaxy of the type and inclination of NGC 1620. In case of a lesser internal reddening the UBR colors of the Hα complexes would reflect a mix of OB type stars superposed on an older stellar population (cf. Larson and Tinsley,
<table>
<thead>
<tr>
<th>HII region</th>
<th>$\Delta x^a$ ($''$)</th>
<th>$\Delta y^b$ ($''$)</th>
<th>$r^c$ ($''$)</th>
<th>aperture radius ($''$)</th>
<th>B</th>
<th>U - B</th>
<th>B - R (erg cm$^{-2}$ s$^{-1}$)</th>
<th>$\text{H}\alpha$ flux (erg s$^{-1}$)</th>
<th>L(\text{H}\alpha) (erg s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-21.9</td>
<td>-52.9</td>
<td>10.7</td>
<td>2.5</td>
<td>19.62</td>
<td>-0.12</td>
<td>1.22</td>
<td>4.09E-15</td>
<td>1.0E+39</td>
</tr>
<tr>
<td>2</td>
<td>-26.4</td>
<td>-56.3</td>
<td>16.2</td>
<td>3.2</td>
<td>18.84</td>
<td>-0.23</td>
<td>1.10</td>
<td>7.16E-15</td>
<td>1.8E+39</td>
</tr>
<tr>
<td>3</td>
<td>-28.4</td>
<td>-48.2</td>
<td>13.8</td>
<td>3.2</td>
<td>18.70</td>
<td>-0.25</td>
<td>1.12</td>
<td>8.50E-15</td>
<td>2.1E+39</td>
</tr>
<tr>
<td>4</td>
<td>-25.9</td>
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<td>14.3</td>
<td>4.2</td>
<td>18.10</td>
<td>0.11</td>
<td>1.21</td>
<td>1.24E-14</td>
<td>3.1E+39</td>
</tr>
<tr>
<td>5</td>
<td>-8.3</td>
<td>-33.4</td>
<td>13.3</td>
<td>2.7</td>
<td>18.92</td>
<td>0.16</td>
<td>1.33</td>
<td>2.78E-15</td>
<td>6.9E+38</td>
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<tr>
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<tr>
<td>A</td>
<td>-25.6</td>
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<td>27.5</td>
<td>4.0</td>
<td>18.01</td>
<td>-0.49</td>
<td>1.04</td>
<td>2.07E-14</td>
<td>5.2E+39</td>
</tr>
<tr>
<td>B</td>
<td>5.8</td>
<td>-19.4</td>
<td>32.9</td>
<td>3.7</td>
<td>18.00</td>
<td>-0.13</td>
<td>1.22</td>
<td>1.49E-14</td>
<td>3.7E+39</td>
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<td>-14.2</td>
<td>39.3</td>
<td>2.7</td>
<td>18.53</td>
<td>-0.34</td>
<td>1.09</td>
<td>8.28E-15</td>
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<tr>
<td>D</td>
<td>-34.9</td>
<td>-52.3</td>
<td>21.3</td>
<td>2.7</td>
<td>19.50</td>
<td>-0.63</td>
<td>0.99</td>
<td>5.28E-15</td>
<td>1.3E+39</td>
</tr>
<tr>
<td>F</td>
<td>-15.3</td>
<td>7.2</td>
<td>52.1</td>
<td>2.2</td>
<td>19.52</td>
<td>0.19</td>
<td>1.29</td>
<td>3.30E-15</td>
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<td>G</td>
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<td>-26.1</td>
<td>24.2</td>
<td>4.2</td>
<td>17.99</td>
<td>0.15</td>
<td>1.32</td>
<td>1.43E-14</td>
<td>3.6E+39</td>
</tr>
</tbody>
</table>

Star cluster at the center of the arc

| -14.9     | -44.9             | 0                  | 1.0        | 20.70          | -0.24 | 1.07    | 7.72E-17       | 1.9E+37    |
|           |                   |                    | 2.0        | 19.19         | -0.26 | 1.01    | 5.68E-16       | 1.4E+38    |
|           |                   |                    | 3.0        | 18.36         | -0.23 | 1.00    | 1.39E-15       | 3.5E+38    |
|           |                   |                    | 4.0        | 17.85         | -0.17 | 1.01    | 2.42E-15       | 6.0E+38    |
|           |                   |                    | 4.9        | 17.49         | -0.09 | 1.05    | 2.79E-15       | 7.0E+38    |
|           |                   |                    | 5.9        | 17.20         | -0.03 | 1.08    | 3.43E-15       | 8.6E+38    |
|           |                   |                    | 6.9        | 16.95         | 0.02  | 1.11    | 4.05E-15       | 1.0E+39    |
|           |                   |                    | 7.9        | 16.73         | 0.07  | 1.13    | 4.79E-15       | 1.2E+39    |
|           |                   |                    | 8.9        | 16.53         | 0.10  | 1.14    | 5.85E-15       | 1.5E+39    |
|           |                   |                    | 9.4        | 16.43         | 0.11  | 1.15    | 7.02E-15       | 1.8E+39    |
|           |                   |                    | 9.9        | 16.34         | 0.12  | 1.15    | 8.72E-15       | 2.2E+39    |
|           |                   |                    | 10.9       | 16.15         | 0.13  | 1.16    | 1.42E-14       | 3.5E+39    |
|           |                   |                    | 11.9       | 15.97         | 0.12  | 1.16    | 2.07E-14       | 5.2E+39    |
|           |                   |                    | 12.8       | 15.80         | 0.12  | 1.15    | 2.70E-14       | 6.8E+39    |
|           |                   |                    | 13.8       | 15.64         | 0.12  | 1.15    | 3.47E-14       | 8.7E+39    |
|           |                   |                    | 14.8       | 15.50         | 0.12  | 1.14    | 4.36E-14       | 1.1E+40    |
|           |                   |                    | 15.8       | 15.37         | 0.12  | 1.14    | 5.19E-14       | 1.3E+40    |
|           |                   |                    | 16.8       | 15.26         | 0.14  | 1.15    | 5.78E-14       | 1.4E+40    |
|           |                   |                    | 17.8       | 15.16         | 0.15  | 1.15    | 6.21E-14       | 1.6E+40    |

Nucleus of galaxy

| 0 | 0 | 47.3 | 4.9 | 15.98 | 0.82 | 1.56 |

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*a* Offset to the East from the center of the galaxy in cartesian coordinates

*b* Offset to the North from the center of the galaxy in cartesian coordinates

*c* Radial distance from the central star cluster
The central star cluster has UBR colors similar to those of the other HII regions in NGC 1620. There is no correlation between quantities such as Hα luminosity, Hα surface brightness, L(Hα)/L_B, position of the knot with respect to the arc, etc... and UBR colors.

The nucleus of NGC 1620 has UBR colors typical of an old stellar population. On a U-R color image (Fig. 6) the central region of NGC 1620 is distinctly redder than the rest of the galaxy and shows evidence for some dust patches N-E of the center.

### 3.3. Hα luminosity versus diameter

In Figure 9 we have plotted Hα luminosity against diameter. For comparison the results for HII regions in nearby galaxies (Kennicutt 1984) are also shown, with Hα luminosities corrected for internal extinction.

A least squares fit to Kennicutt’s data yields a line of slope 3.5 (solid line in Fig. 9). Fitting a line of the same slope to the NGC 1620 data yields a zero-point shift of 2.25, which corresponds to an increase by a factor 4.4 in diameter at a given luminosity. As NGC 1620 is considerably more distant than the galaxies in Kennicutt’s (1984) sample, it is likely that our bright Hα concentrations are a collection of individual HII regions. If each Hα knot of diameter D and internal extinction-corrected luminosity $L_e = A L_{\text{obs}}$ (with $A$ the extinction factor and $L_{\text{obs}}$ the observed Hα luminosity) consists of $N$ individual HII regions of diameter $d$ and luminosity $l$ with a net surface filling factor $f$, we have the relations $N \pi d^2 = f \pi D^2$ and $l = A L_{\text{obs}}/N$. Imposing the constraint that the individual HII regions obey the same luminosity-diameter relation as those in nearby galaxies, we obtain the relation $(N/f)^{1/2} N^{-1/a} = 4.4 A^{-1/a}$, with $a = 3.5$ the slope of the luminosity-diameter relation.

We consider two extreme cases: no internal extinction ($A = 1$) and the maximum internal extinction allowed by the UBR colors ($A = 5$). For $N = 5$ and $A = 5$ the luminosities remain unchanged, the diameters decrease by a factor 4.4 and $f = 0.26$. For $N = 5$ and $A = 1$ the luminosities and diameters decrease by a factor of 5 and 7, respectively, and $f = 0.1$. In the first case we retain the three giant HII regions, in the latter case none. We conclude that if we allow for moderate internal extinction and lack of resolution, the number of giant HII regions in NGC 1620 is less than 3, which is consistent with the average frequency of 0.1 and 0.6 giant HII regions per Sb and Sc galaxy, respectively, found by Kennicutt and Chu (1988). On the other hand, the central star cluster has likely been a giant HII region at the time of its peak activity.

### 3.4. Characteristics of the arc-like feature and its central star cluster

An obvious question is to what extent the arc is partial or a complete circular feature. In an attempt to establish this we have constructed a U-R color image (Fig. 6) and unsharp masked images (Fig. 10) which should enhance low surface brightness features. The U-R color image does bring out the ‘missing’ part of the arc and gives the impression of a full circular feature that, in contrast to its appearance on the unsharp masked U, B and R images, is faintest in the direction toward the center of the galaxy. The ring is everywhere bluer than its surroundings. The unsharp masked R image is obtained by dividing the original image by that convolved with a gaussian kernel of sigma 3′′ and reduced in intensity by a factor of 0.75. Such an image effectively reveals faint irregularities concealed by the (subtracted) global light distribution. In this case it shows a more diffuse version of the lumpy arc seen against the disk of NGC 1620 on our U image as well as a fainter ridge that completes the circle. This ridge shows region 6 and two fainter adjacent clumps as local luminosity enhancements and runs across the dust lane at very low surface brightness (which is seen much better on the original image than on the print reproduced here). Some low surface brightness features are also visible within the circle. The spiral arm containing regions B, C and G cuts across the circle at lower surface brightness and seems to end in knot 7. Two faint wisps seem to emanate from the central star cluster, one to the North which reaches the arc near knot 5 and one to the South which ends in knot 7. The wisps do not seem to be part of a spiral arm. Since a supernova bubble event affects the surrounding gas but not the stars the presence of spiral arms or other features associated with the older stellar population within the bubble region is expected. An unsharp masked B image looks very similar but has less contrast than the unsharp masked R image because the B image is less deep and the B continuum is a relatively less strong component. For the same reasons an unsharp masked U image is even less informative.

### 4. Discussion

CV91 proposed that the giant arc in NGC 1620 is the result of a supernova-blown bubble whose shell became gravitationally unstable and formed stars. On the basis of models of superbubbles (Mac Low and McCray 1988, McCray 1988), they argued that an energy injection by 7000 supernovae over a period of $7.6 \times 10^6$ yr, yielding a final velocity of the shell at
the time of star formation of 50 km s$^{-1}$, accounts best for the current size of the arc. In the light of our new observational results, we reconsider the ‘supergiant bubble’ interpretation of the arc here in some more detail.

4.1. The supergiant bubble scenario

The young star cluster at the center of the arc stands out as the brightest and most extended condensation in continuum light besides the nucleus of the galaxy (cf. Table 2). While the spiral arms of NGC 1620 are well delineated by bright condensations in continuum light, this star cluster is obviously not part of a spiral arm as we would expect it to be if it were a ‘normal’ HII-region complex (for example, the supergiant HII regions in M101 all obviously lie in spiral arms). On our U and B images the annulus in between the central cluster and the arc is remarkably ‘empty’ of any features superposed on the background continuum. Our unsharp masked R image dramatically illustrates the prominence of the cluster against a background of stellar spiral arms and faint wisps which would of course not have been affected by any relatively recent supernova events. Because of its unique and isolated location at the center of the arc and its large luminosity, it seems most likely that the young star cluster itself is responsible for its unusual environment within the galaxy. On the basis of its redshift, its diffuseness that is characteristic of a young star cluster rather than of a galaxy nucleus, and the stability arguments discussed by CV91, it can be ruled out that the blue clump is an intruder or an accreting companion of NGC 1620. The most likely interpretation therefore is that the star cluster has been the site of a large number of supernova explosions that swept up the surrounding gas into an expanding shell which became gravitationally unstable and formed stars. The fact that the central star cluster consists of at least three lumps makes it plausible that a continuous supernova input over several generations of stars has occurred.

A sustained energy input would have been extremely favorable for the formation of a supershell. Such a shell is three-dimensional. If the central star cluster is located in the mid-plane of the galaxy, the expanding gaseous shell will remain roughly spherical as long as its radius does not exceed one vertical scale height of the ambient gas. At larger radii the shell would expand more rapidly in the vertical direction, acquiring a prolate shape. The distension of the shell in the vertical direction would result in a final appearance of the shell as a ring in the plane of the galaxy with a terminal radius of about two gas scale heights (McCray 1988). In the case of NGC 1620, projection effects due to the $\sim 70^\circ$ inclination of the disk would result in an ellipse with axial ratio $\sim 3$. Our U frame (Fig. 2) clearly shows that the arc, if elliptic at all, appears much less elongated than the spiral arms and inner regions of the disk. The implication is that the arc is a 3-dimensional shell rather than a ring so that the expanding HI shell must have become unstable and formed stars before breaking out of the galactic disk. On the other hand, the arc, with two noticeable kinks (near Ho knot 3 and in between knots 4 and 5) and hardly visible in continuum light to the South-East, is not perfectly circular and is distinctly asymmetric in surface brightness. Given the presence of a strong gradient in optical continuum light and of faint spiral arms (Fig. 10), we speculate that large-scale gradients and inhomogeneities in the density of the ambient gas are most likely responsible for this, e.g., the faintness of the arc in the direction away from the center of the galaxy is most likely caused by a negative radial gradient in the gas density while the kinks may be due to encounters with gas clouds in the nearest spiral arms.

The dust lane in the disk of NGC 1620 (Figs. 1, 2, 10), at a projected minimum distance of 7.5′′ from the center of the star cluster, appears unperturbed. This implies that the expanding shell must have formed stars when it had a radius smaller than 1.7 kpc, or about half its current size. The fact that the arc is seen to run across the dust lane in continuum light (Fig. 10) is consistent with this scenario.

4.2. The arc as the stellar remnant of a supernova-blown bubble

At early times a continuous supernova energy input keeps the interior of a bubble pressurized and drives the expansion of the shell until a time $t_1$ at which gravitational instabilities set in, leading to star formation (cf. McCray 1988). The time $t_1$ and the corresponding radius and velocity of the shell can be written as

$$
t_1 \approx 1.3 \times 10^7 L_{39}^{-1/8} n_o^{-1/2} a_{39}^{5/8} \text{ yr} \tag{2}
$$

$$
R_1 \approx 500 L_{39}^{1/8} n_o^{-1/2} a_{39}^{3/8} \text{ pc} \tag{3}
$$

$$
V_s \approx 22.5 L_{39}^{1/4} a_{39}^{-1/4} \text{ km s}^{-1} \tag{4}
$$

with $L_{39}$ the power input by supernovae in units of $10^{39}$ erg s$^{-1}$, $n_o$ the atomic number density of the ambient gas —assumed to be uniform— in units of cm$^{-3}$ and $a_s$ the magneto-sound speed in the shell in units of km s$^{-1}$. The supernova power input is given by $L = \epsilon E_{39}$, with $\epsilon$ the supernova frequency and $E_{39}$ the energy per supernova, so that $L_{39}$ corresponds
α

On the basis of their UBR colors, the H

than those HII regions on the basis of its weaker H

consistent with the fact that the blue clump seems older than the stars and HII regions in the arc. This is con-

cluster at the center of the arc is older by \( t > t_1 \), the now stellar shell continues expanding at constant velocity \( V_s \) provided that \( V_s > 20 \text{ km s}^{-1} \) (expansion velocities of \( \sim 20 \text{ km s}^{-1} \) are typical of 1 kpc large HI supershells in our Galaxy (Heiles 1979)). The radius of the shell becomes \( R(t) = R_1 + V_st \). The constraint on \( V_s \) requires a supernova power input \( L_{39} > 1 \), and, for \( n_o \approx 1 \text{ cm}^{-3} \), yields a minimum radius \( R_1 \approx 500 \text{ pc} \) and a maximum possible age of the stars in the shell of \( 1.3 \times 10^8 \text{ yr} \), while \( t_1 \) (eq. [2]) remains smaller than the lifetime \( \sim 5 \times 10^7 \text{ yr} \) of a type B3 star, the least massive supernova progenitor, so that one coeval generation of stars can assure a continuous power supply. The total number of supernovae required in this case would be \( > 400 \). On the basis of their UBR colors, the H\( \alpha \) knots in the shell could consist of a single generation of OB stars or be a stellar population mix with a wider age range, the uncertainty being due to the unknown internal extinction. In the extreme case of OB stars only, the age of the stars in the shell should be less than \( 5 \times 10^7 \text{ yrs} \), which is the lifetime of the least massive ionizing star, of type B3. This would require an expansion velocity of \( 50 \text{ km s}^{-1} \) implying a supernova power of \( L_{39} \approx 24 \) injected over \( 8.7 \times 10^6 \text{ yr} \), or \( 6500 \text{ supernovae} \). This is comparable to the number of supernova progenitors in the largest OB associations in our Galaxy, as estimated from the ionizing radiation of radio HII regions (Heiles 1990, McKee and Williams 1993). This case yields a maximum radius of the gaseous shell, \( R_1 \approx 750 \text{ pc} \), which is comparable to that of the HI supershells found in our Galaxy. Larger supernova energy inputs would yield larger \( V_s \) and \( R_1 \), and a smaller age in the shell. Because the gas crossing time of a cavity of radius \( R_1 \), \( \tau = 5 \times 10^7 (R_1/500 \text{ pc}) (v_{\text{gas}}/10 \text{ km s}^{-1}) \text{ yr} \), is comparable to the total time elapsed since the onset of the formation of the postulated superbubble this cavity would no longer exist as a hole in the HI distribution of NGC 1620 unless supernova activity has been sustained at times \( t > t_1 \).

According to the above superbubble scenario the cluster at the center of the arc is older by \( \sim 10^7 \text{ yr} \) than the stars and HII regions in the arc. This is consistent with the fact that the blue clump seems older than those HII regions on the basis of its weaker H\( \alpha \) emission (Table 2). If the blue clump is a supergiant star cluster or a complex of star clusters that originally formed within a spiral arm, then the explosion of a large number of supernovae must have evacuated the surrounding region, and the accumulating gas swept up by an expanding bubble would have run into and distorted the gas trapped in the nearest spiral arms. The diffuse H\( \alpha \) emission near the central star cluster can be due to gas initially associated with that cluster or newly acquired gas by thermal evaporation within the hot bubble. We note that much of the above discussion depends on the ambient gas density being of order 1 cm\(^{-1}\), a value which would appear to be rather large for gas \( \sim 500 \text{ pc} \) from the plane. However, we note that CO measurements in NGC 891 by Scoville et al. (1993) indicates that the gas in that galaxy has twice the scale height of the gas in our own Galaxy. The existence of the shell may be taken as an indication that the HI layer is much thicker in NGC 1620 than our Galaxy.

The inside of the bubble seems remarkably smooth and ‘empty’ except for the underlying continuum light of the older stellar population, including spiral arms and two faint wisps (Fig. 10). This suggests that all gas initially present has been swept up or, in case of denser clouds, thermally evaporated in the hot bubble interior. The cooling time of the hot bubble interior, \( t_c \approx 3 \times 10^7 L_{39}^{-3/11} n_o^{-8/11} \text{ yr} \) (Mac Low and McCray 1988), is smaller than the time elapsed since the formation of the bubble so that, unless supernova explosions continued after the onset of star formation in the expanding shell, the bubble interior has cooled and is no longer observable in soft X-rays.

The swept up mass,

\[
M \approx 1.3 \times 10^7 R_{500}^3 n_o M_\odot
\]

where \( R_{500} \) the radius \( R_1 \) in units of 500 pc, is comparable to the HI masses found in supershells in the Milky Way and other galaxies (cf. van der Hulst and Kamphuis 1991), while the typical mass of a gravitationally unstable fragment

\[
M \approx 1.3 \times 10^5 L_{39}^{-1/8} n_o^{-1/2} a_s^{29/8} M_\odot,
\]

(McCray 1988) is a hundred times smaller and comparable to the mass of a large molecular cloud in the Galaxy.

4.3. The location of the arc and the local structure of the galactic disk

Because of the overall remarkably circular shape of the arc, the distinct asymmetry in surface bright-
ness of the arc in NGC 1620 presumably reflects the radial gradient of the gas density along the galactic disk rather than a partial break-out of the original shell from the gaseous disk. If no break-out occurred, then the size of the shell in its gaseous state has not exceeded a few scale heights of the gaseous layer (Mac Low et al. 1989). It follows that the gas scale height at the location of the arc should be of the same 0.5−1 kpc order as the values derived above for $R_1$. By analogy with two well-studied Sb galaxies, our Galaxy and the edge-on spiral NGC 891, this is quite a reasonable result. The galactocentric distance to the center of the arc of 11.1 kpc is somewhat larger than that of the solar neighborhood in our Galaxy. The scale height of the neutral HI gas in the solar neighborhood is $\sim 200$ pc (and likely a factor of two large in NGC 891 Scoville et al. 1993) and known to increase rapidly with increasing distance, up to 500−1000 pc beyond the solar circle (e.g., Kulkarni et al. 1982). Such an increase is expected from a decreasing net surface mass density of the disk to which the gas scale height is inversely proportional (cf. Vader and de Jong 1981). The surprisingly large size of many supershells has emphasized the importance of a low-density tail of HI gas at high heights above the plane of our Galaxy originally discovered by Shane (1971), and of the extended diffuse ionized layer of gas with a typical scale height of 1 kpc, discovered by Reynolds (1990) in our Galaxy and detected in other nearby spiral galaxies such as NGC 891 (Rand et al. 1990; Dettmar 1990). The existence of this ionized layer and that of superbubbles, shells, worms and chimneys (Heiles 1990) are believed to be inter-dependent, the latter forming the channels through which the ionizing photons escape confinement within the disk and the gas acting as a confinement agent up to large vertical distances from the disk (Mac Low et al. 1989, Norman and Ikeuchi 1989, Norman 1991). The fact that all supershells in our Galaxy are located beyond the solar circle offers indirect support of the confining effects and outwardly increasing scale height of the gaseous layer. No correlation between HI shells and OB associations or HII regions has been found in the Galaxy (Heiles 1979, 1984). In contrast, the stellar arc in N1620 is remarkable because of the very luminous blue star cluster at its center which must be at its origin. At the location of the bubble, the disk surface brightness presents a strong gradient in the N-S direction which presumably reflects the radial gradient in surface mass density, implying a strong increase outwards of the gaseous scale height.

The annulus around the central star cluster and within the arc, which is devoid of any local features above our detection limit except for faint stellar spiral arms and wisps, has colors $B-R = 1.45$ and $U-B = 0.2$ (Table 2) and an R surface brightness of 21.5 mag arcsec$^{-2}$, yielding a B surface brightness corrected for inclination and internal extinction of 23.8 mag arcsec$^{-2}$. These values are typical of the inter-arm regions of the disks of spiral galaxies (Schweizer 1976). The colors also fit in a sequence of stellar population models with decreasing star formation rates and age $10^{10}$ yr (Larson and Tinsley 1978) and suggest a mass-to-light ratio of the stellar population of $M/L_B \sim 2$ to 3. These results indicate that the arc can be explained as the product of a superbubble under totally ordinary circumstances in which the disk of NGC 1620 has a structure typical of the outer regions in spiral galaxies.

4.4. NGC 1620 as an ordinary SBbc galaxy

Except for its giant arc, NGC 1620 appears to be a normal SBbc galaxy. An inspection of our optical broad-band images shows that overall light distribution in the disk of NGC 1620, at the galactocentric distance of the arc and beyond, is very symmetric with respect to the center of the galaxy. Hence the underlying older stellar population is not affected by the presence of the clump. A global HI flux measurement yields a total HI mass of $1.1 \times 10^{10}$ solar masses and a hydrogen mass to luminosity ratio $M_H/L_B = 0.35$ (Shostak 1978) that are typical for an Sbc galaxy. We have commented above upon the number of giant HII regions in NGC 1620 (Sect. 3.3). In the case of NGC 891, an edge-on Sb galaxy, it is remarkable that, in spite of the scarcity of giant HII regions—the sites of powerful supernova explosions—in Sb galaxies (Kennicutt and Chu 1988), an extended layer of ionized gas with a scale height of order 1 kpc has been detected in Hα (Rand et al. 1990; Dettmar 1990) as well as possibly evidence for outflow of gas from the disk through chimneys (Norman and Ikeuchi 1989). This galaxy must therefore have a disk-halo connection powered by star formation. NGC 1620 may be another example of such a galaxy. The presence of what is most likely the remnant of a superbubble that region that is responsible for the creation of a superbubble and the observed arc is then not so surprising. Either NGC 1620, NGC 891 and our Galaxy, all of which show features believed to be associated with the occurrence of giant HII regions, have a larger number of giant HII regions than expected for Sb-Sc galaxies, or the numbers found by Kennicutt and Chu (1988) on the basis of ten Sb and fifteen Sc galaxies are not representative, or ordinary HII regions are sufficient to sustain a disk-halo connection.
5. Conclusions

Our UBR and Hα imaging of NGC 1620 shows that the smooth arc visible on the POSS print and on an earlier CCD B image (CV91) consists of a young stellar population and contains several HII region complexes. On a U-R and an unsharp masked R image, a faint ridge of continuum light is detected on the East side and completes the arc into a ring. We have established that the clump at its center is a very luminous star cluster which, given its relatively weaker Hα emission, is presumably somewhat older than the stars in the arc. Our new data support the hypothesis of CV91 that the arc is a supernova-induced supershell that formed stars. We have considered two extreme possibilities constrained by the survival of the expanding arc against random stellar motions and the age of the stars in the arc. Requiring a minimum expansion velocity of 20 km s\(^{-1}\) yields an energy input from > 400 supernovae over a time scale of 1.3 × 10\(^{7}\) yr, a lower limit of 500 pc for the radius of the HI shell at the onset of star formation and a maximum age of the stars in the arc of 1.3 × 10\(^{8}\) yr. At the other extreme, requiring an age of the stellar arc of less than 5 × 10\(^{7}\) yr —the lifetime of the least massive ionizing star— yields an expansion velocity of the arc of 50 km s\(^{-1}\), an energy injection by 6500 supernovae over 8.7 × 10\(^{6}\) yr, and a radius of the HI supershell of 750 pc. The latter case corresponds to a number of supernova progenitors that is comparable to that estimated for the largest OB associations in our Galaxy. This scenario requires that the NGC 1620 has a much thick layer of HI as compared to our own Galaxy. The maximum radius of the HI shell at the onset of star formation is less than three times the current size of the arc. In this case the hole of similar size created in the HI distribution by the superbubble no longer exists because the time elapsed since its formation exceeds the gas crossing time. On the other hand, depending on the efficiency of star formation, an HI enhancement might still be visible at the location of the arc. Because NGC 1620 is a not quite edge-on galaxy at a relatively large distance, a study of its vertical disk structure, e.g., the detection of a thick disk of ionized gas, is difficult. However, high resolution radio continuum observations are desirable for a determination of the internal extinction of the HII regions in the arc which would yield a better estimate of the ionizing flux and of the average age of the ionizing stars from extinction-corrected optical colors. It would also be interesting to try to determine the current expansion velocity of the arc with, e.g., Fabry-Pérot observations in Hα.

The location of the arc in the outer disk of the galaxy, at about 11 kpc from the center, is typical of that of HI supershells in other spiral galaxies where their existence is favored by gas with large scale heights that acts as a confining agent. The circular shape of the arc in the highly inclined disk of NGC 1620 suggests that blow-out during the gaseous phase has not occurred to a significant degree. What is unusual about the arc-like feature in N1620 is its stellar nature and the presence of the luminous star cluster at its center. We do not know of similar configurations in other galaxies. NGC 1620 is an otherwise unremarkable SBbc galaxy.

In conclusion, the large scale arc and its central star cluster in NGC 1620 present an interesting test case for current ideas on supergiant shells and associated features and how they establish a disk-halo connection.

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FIGURE CAPTIONS

FIG. 1: 125″ × 125″ B image on a linear intensity scale. North is up and East is to the left.

FIG. 2: U image (Nov 21) on a linear intensity scale. Size and orientation same as in Fig. 1.

FIG. 3: a) Hα line emission image on a linear intensity scale. Size and orientation same as in Fig. 1. The brightest condensations are identified. The circle of radius 14″ indicates the position of the arc. b) An overlay of a) identifying the Hα knots (open circles for knots 1 to 6, triangles for knots A to G), the central star cluster and the nucleus of the galaxy (crosses), and the same circle as in a). This overlay can also be used for Figs. 1, 2, 6 and 11.

FIG. 4: Spectrum of the star cluster at the center of the arc and of the nucleus of NGC 1620. The vertical lines identify the CaII K and H lines in absorption and Hα in emission. Hβ is seen in both absorption and emission for the star cluster.

FIG. 5: A contour plot of the R intensity on a linear scale, centered on the blue clump. The intensity of the contours decreases in steps of 150 counts, from 5277 to 4077 counts/pixel, which corresponds to an observed surface brightness range (not corrected for extinction) of 20.83 to 21.75 mag arcsec$^{-2}$. The spatial scale shown is in pixels (0.494″/pixel).

FIG. 6: Color map U-R on a logarithmic intensity scale. Size and orientation same as in Fig. 1.

FIG. 7: Average Hα surface brightness (corrected for foreground extinction) against radius of the knots in NGC 1620 (open circles for knots 1 to 6; triangles for knots A to G ) and the differential Hα surface brightness profile centered on the star cluster at the center of the arc (dots). Note that the center of the star cluster has been defined on the B frame, and that there is strong off-centered Hα emission (Fig. 3), so that the peak Hα intensity in the star cluster does not correspond to 0 radius.

FIG. 8: UBR color-color diagram, with colors corrected for foreground extinction. Open circles represent knots 1 to 6; triangles knots A to G and the two dots represent circular apertures of 5″ radius centered on the blue clump and on the nucleus of the galaxy (cf. Table 2). The solid curve is defined by main-sequence stars from type O9.5 to K5, the dotted curve by giant stars of type G5 to K1 (Johnson 1966). The arrow is a reddening vector of a length corresponding to $E(B-V) = 0.5$.

FIG. 9: Hα luminosity (erg s$^{-1}$) corrected for foreground extinction against diameter (pc) for the Hα knots of NGC 1620 listed in Table 2 (open circles for knots 1 to 6; triangles for knots A to G ). The diamonds represent extragalactic HII regions with Hα luminosity corrected for foreground and internal extinction (Kennicutt 1984; his Table 2). The solid lines represent linear square fits to the data, with a slope of 3.5, determined from Kennicutt’s data. The dotted line shows the location the HII regions in NGC 1620 would have if the Hα knots were resolved in 4 individual HII regions with a surface filling factor of 50% (see text).

FIG. 10: An unsharp masked R image obtained by dividing the original R image by the R image convolved with a gaussian kernel of sigma 3″ and reduced in intensity by a factor 0.75. The size is 195″ × 195″. The scale, the orientation and the circle are the same as in Fig. 3.