SEPARATING C STARS FROM DUST IN THE CENTRAL REGION OF THE SEYFERT 2 GALAXY NGC 1241

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ABSTRACT

The Seyfert 2 galaxy NGC 1241 presents a 1.5 kpc large circumnuclear ring (CNR) of star formation embracing a small bar plus leading arms. Those structures are Paα emitters but barely seen in Hα. It also presents stellar trailing arms inside the CNR. Gemini and *HST* imagery allow the construction of high-resolution $(V - H)$ and $(J - K_s)$ color maps, as well as a $(J - K_s)$ versus K color-magnitude diagram of this complex region. The CNR is heavily obscured in V, but a fairly transparent window appears in the direction of the nucleus. Nonetheless, the nucleus presents a $(J - K_s)$ color that is redder than the CNR. The CNR is composed of extremely young H II regions still enshrouded in their dust cocoons. However, the nuclear $(J - K_s)$ color cannot be explained in this manner. Therefore, we propose the contribution of C stars as the most feasible mechanism for explaining the colors. If the nuclear stellar population is comparable to that of the Large Magellanic Cloud bar, 500 C stars and 25,000 asymptotic giant branch O-rich stars inside 50 pc may reproduce the observed colors. C stars release enriched material to the nuclear environment, probably fueling the central engine of this Seyfert 2 galaxy during the lifetime of stars with masses in the range $2\,M_\odot < M_{\rm C\,star} < 6\,M_\odot$ (C-star phase). The ejected material that remains trapped in the central potential might also explain the systematically observed increased strength of the optical CN bands in Seyfert 2 galaxies and is consistent with the significant contribution of intermediate age stars to the optical continuum of low-luminosity active galactic nuclei.

Subject headings: galaxies: active — galaxies: individual (NGC 1241) — galaxies: ISM — galaxies: nuclei — galaxies: photometry — galaxies: stellar content

1. INTRODUCTION

NGC 1241 is a Seyfert 2 galaxy (Véron-Cetty et al. 1998) that presents a complex morphology in the innermost 1.5 kpc. Paα imagery shows the presence of an emitting circumnuclear ring (CNR) of star formation with a brightness peak at a radius of 710 ± 80 pc. It also shows a 0.3 kpc long bar accompanied by an $m = 2$ leading arm, both emitting in Paα and centered on the nucleus. Apparently, they do not have associated absorption features as might be expected (Regan & Mulchaey 1999, hereafter RM99). The J and K_s images reveal that the CNR is mounted on a smooth inclined disk with approximately elliptical isophotes of varying position angle. The major to minor axis ratio of the outermost isophotes in the J and K_s bands reveals a disk inclination of 52°, consistent with the value given by Tully (1988) for the large-scale disk. Finally, the K_s image shows the presence of a trailing arm ending at the CNR and centered on the nucleus. These structures (Fig. 1) have been kinematically studied by Díaz et al. (2003). RM99 have found that the $(V - H)$ color map to the southwest of the line of nodes of NGC 1241 is redder than in the northeast area and reveals an overall dusty morphology consistent with an inclined ring with a color excess of 1.1 mag, whose southwest side is the nearest one. According to these authors, assuming that the dust scale height is small relative to the scale height of the stars, and that the plane of the dust is inclined with respect to the bulge stars, dust absorption might not affect the color of the bulge near the nucleus. As we see later, the nucleus of NGC 1241 is relatively free of absorption when compared to the color excess of the ring. To reinforce this picture, none of the absorption features normally expected near emitting bars

are evident near the 300 pc long bar found by Díaz et al. (2003). These authors have also shown that the ring of dust found by RM99 coincides with the CNR (Fig. 2).

In this Letter we examine Gemini (+QUIRC+Hokupa) near-infrared (NIR) images with pixel-photometry. We detected the presence of an azimuthally symmetric nuclear $(J - K_s)$ color excess with respect to the CNR [$0.82 < (J - K_s) < 1.15$], which would not be easily explainable in terms of dust absorption according to the aforementioned RM99 results. Moreover, the $(V - H)$ color map does not show azimuthal symmetry as the $(J - K_s)$ one does. The properties of the $(V - H)$ and $(J - K_s)$ in the inner 2 kpc are analyzed in terms of the models of Witt et al. (1992, hereafter WTC92) and the stellar population synthesis from 2MASS NIR color-magnitude diagrams (CMDs) of bar fields in the Large Magellanic Cloud (LMC), where individual stars are resolved at $M_V \leq -3$ (Nikolaev & Weinberg 2000).

The next section of this Letter outlines how our observations were made and discusses the homogenization of *Hubble Space Telescope* (*HST*) and Gemini photometry. In § 3 our results are discussed, and the final remarks are given in § 4.

2. OBSERVATIONS AND METHODS

On 2000 September 30 we used the Quick Start service of the Gemini North 8.1 m telescope for NIR imaging using Hokupa'a natural guide star and curvature-sensing adaptive optics system. The latter feeds the dedicated Quick NIR camera (QUIRC) fitted with a 1024 × 1024 HgCdTe array sensitive to 1–2.5 μm radiation, providing a final scale of 0".0197 pixel⁻¹. Standard data reduction procedures were applied to the images. The achieved FWHM of the Gemini+Hokupa'a system was about 0".4 in the J band and about 0".3 in the K_s band, both measured on the point-spread function of a field star and estimated on the target galaxy. Image deconvolution was not applied at this stage because of the photometric uncertainties that could be introduced by the methods that are commonly used. This

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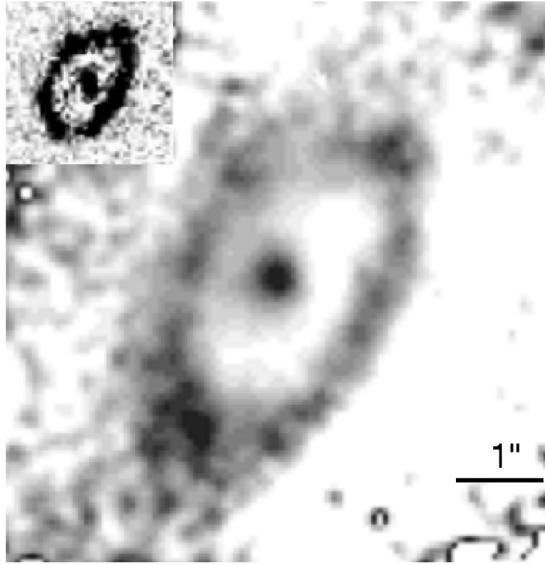
Fig. 1.—Gemini $J - K_s$ differential color map of the central 2×2 kpc region of NGC 1241. North is at the top and east to the left. The darkest areas represent those regions that more strongly depart from a smooth color distribution. The inset shows the *HST* Paα image, after continuum subtraction using the *H* band. Note the barlike central structure and the faint leading spiral in the Paα emission (see Díaz et al. 2003).

resolution was good enough to compare the Gemini images with the existing *HST* NICMOS3 data (Fig. 1).

2.1. *Photometry*

HST imagery with F160W and F606W filters and its calibration have been discussed by RM99. Essentially, the relative fluxes of these frames at each position are given. A transformation was performed in order to match colors derived from the *HST* fluxes f_{F606W} and f_{F160W} to the standard color system of our observations. For filter F606W, we obtained m_{F606W} from the flux f_{F606W} in the Vega-mag system according to Bedin et al. (2005). Coefficients for the transformation of m_{F606W} into V of the Vega-mag system are provided by Holtzman et al. (1995). V results ≈ 0.1 mag brighter than m_{F606W} are in agreement with the previous transformation by Malkan et al. (1995), who determined that V would be 0.1–0.2 mag brighter than m_{F606W}. For filter F160W, we calculated m_{F160W} according to Stephens et al. (2000). These authors follow two different procedures to transform m_{F160W} into H, each providing slightly different results. To be coherent with the transformation of m_{F606W} into V, we adopted the procedure based on the Vega-mag system.

Using homogeneous colors, we carried out pixel photometry to ascertain whether the morphology seen in K_s-band images is differentially affected by the presence of dust. After separating all the pixels to the northeast from those to the southwest of the major axis, we integrated the K_s brightness and $(J - K_s)$ and $(V - H)$ colors on half-rings of variable radii and plotted them against the deprojected radius (Fig. 3).

The WTC92 models of dust and transfer of stellar radiation within galaxies have been used to disentangle color properties due to dust from those due to stellar population effects. WTC92 models include the effect of light scattering by dust. Four of the models presented by these authors constitute plausible scenarios for the region under study: (1) the dusty galaxy, which considers dust and stars equally distributed within a sphere; (2) the cloudy galaxy, which considers the sphere occupied by stars to be larger than that occupied by dust; (3) the starburst galaxy, in which also stars occupy a larger sphere than the dust but
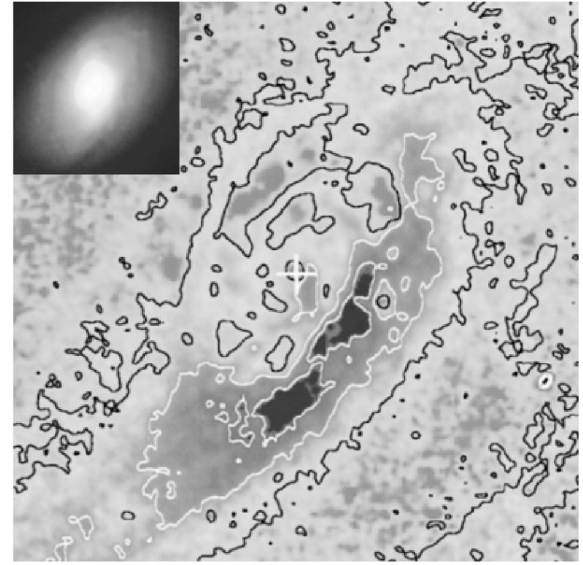

Fig. 2.—Color map made by combining the NICMOS 1.6 μm image with a *HST*-WFPC2 F606W image (RM99). The contours of the F606W-F160W red color excesses (compared with the background galaxy) are at magnitude 0.3, 0.6, 0.9, and 1.2. The field shows the central 2×2 kpc region of NGC 1241. North is at the top and east to the left. The inset shows the *H*-band (F160W) image.
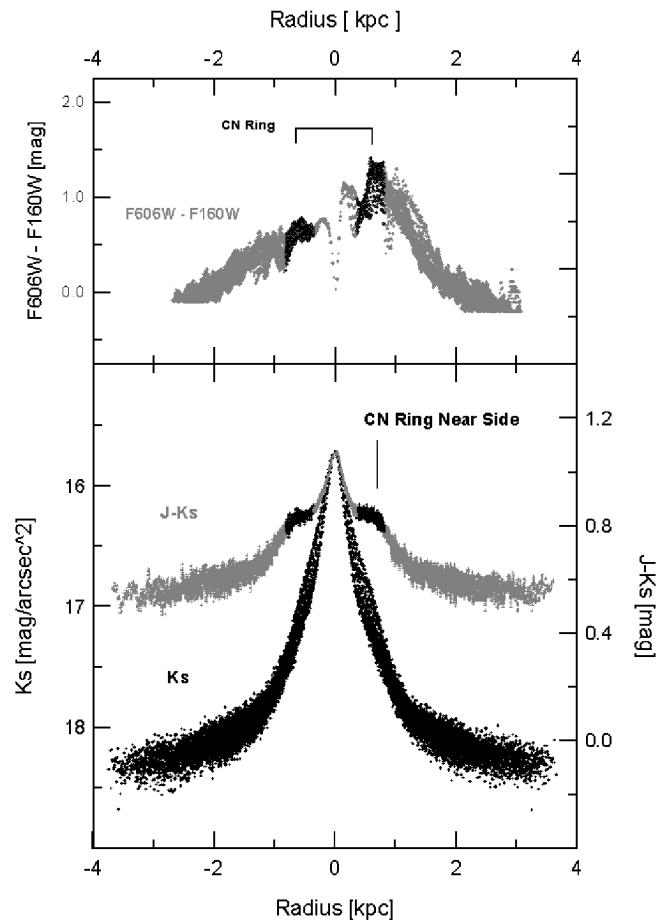

Fig. 3.—$V - H$ (*upper panel*) and K_s and $J - K_s$ (*lower panel*) band photometric values for $0\farcs1$ rebinned pixels plotted against the deprojected radius. Pixels to the northeast are separated from those to the southwest of the major axis (positive radii). The pixels in the radial range corresponding to the CNR were plotted as black points in the color profiles. Note the increasing reddening inward, and the remarkably similar radial behavior of the $J - K_s$ color profile on both sides of the line of nodes.

TABLE 1
NGC 1241 Colors and Relative Fluxes

Structure	$(V - H)$ $(m_{F606W} - m_{F160W})$	$(J - K_s)^a$ $(m_{110W} - m_{F222W})$
Disk (outward CNR) ……	−0.1 ± 0.2 **0.0 ± 0.2**	**0.55 ± 0.1**
CNR (near side) ………	1.5 ± 0.2 **1.35 ± 0.2**	**0.82 ± 0.06**
CNR (far side) ………	0.61 ± 0.1 **0.6 ± 0.05**	**0.82 ± 0.06**
Nucleus ………………	0.0 ± 0.1 **0.0 ± 0.1**	**1.05 ± 0.03**

^{a} J and K_s are standard colors observed with Gemini; m_{F606W} and m_{F160W} are derived from *HST* fluxes. Observed quantities are in bold.

follow an r^{-6} distribution; (4) the dusty galactic nucleus, in which a sphere of stars is enshrouded in a cocoon of dust.

Errors in colors for each one of the subsystems quoted in Figure 3 are directly obtained from fluctuations in pixel photometry and propagated to the derived quantities according to the transformation equations of the photometric system.

3. RESULTS AND DISCUSSION

Figure 3 shows that the $(J - K_s)$ reddening increases inward, as well as a remarkably similar radial behavior on both sides of the line of nodes. It also shows a plateau at $(J - K_s) \approx 0.8$ mag at the position of the CNR, with a maximum of about 1.15 mag in the nucleus. The K_s-band integrated profile is also symmetric. On the other hand, the upper panel of Figure 3 shows how dramatically different are both sides of the circumnuclear ring in the $(V - H)$ color, with an excess $E(V - H) \approx 1.0$ in the southwest side with respect to the northeast one, besides a global mean color excess $\langle E(V - H) \rangle \approx 0.90$ of the CNR with respect to the disk. The nucleus is also remarkable, as its $(V - H)$ color is similar to that of the disk outside the CNR, indicating the presence of a transparent window in that direction, as suggested by RM99. This conclusion is corroborated by the detection of nuclear Hα emission (the galaxy is a Seyfert 2) together with Paα emission, while the CNR is observed in Paα but obscured in Hα.

Colors in Table 1 can be matched to stellar spectral types using the Pickles (1998) stellar library. The results are quoted in Table 2. We first note that the $(V - H)$ colors of all substructures in Table 1 correspond to younger spectral types than would be indicated by the $(J - K_s)$ color, in spite of the stronger reddening in the V band.

3.1. The Disk

Its $(J - K_s)$ color is similar to the color in the foreground of the LMC fields studied by Nikolaev & Weinberg (2000) and the Sagittarius comparison fields studied by Cole (2001), both obtained from the Two Micron All Sky Survey (2MASS) data. We obtained similar results by integrating six Milky Way fields around the LMC, as we show in the results. Nevertheless, the disk $(V - H)$ color corresponds to a B9 V–A2 V stellar population, which leads us to think that star formation occurred not only in the CNR but also reached the inner disk within its innermost 2 kpc.

3.2. Circumnuclear Ring

Assuming that the difference in the observed $(J - K_s)$ between the far side of the CNR and the disk is caused by extinction, we obtain $E_{fs_o}(J - K_s) \approx 0.30$, mag and the WTC92 dusty galaxy model leads to an extinction solution with

TABLE 2
Stellar Spectral Types in Pickles (1998)
Stellar Library That Match the Colors
in Table 1

Structure	$(V - H)$	$(J - K_s)$
Disk (outward CNR) ……	B9 V–A2 V	K0–K2
CNR (near side) ………	G2 V–G5 V	M2–M4
CNR (far side) …………	F0 V–F2 V	M1–M2
Nucleus …………………	A3 V–A5 V	M5–M6

$\tau_V = 6.0$ and scattered light contributing 45% in V band. This model provides theoretical color excesses for the CNR far side amounting to $E_{fs_t}(J - K_s) = 0.30$ mag and $E_{fs_t}(V - H) \approx 0.7$, coherent with the values presented in Table 1. This source of absorption, probably diffuse, is intrinsic to the CNR and different from that discussed by RM99, which produces the difference in $(V - H)$ between the CNR near and far sides, attributed to the dusty one-arm clearly seen in the *HST* F606W filter image by RM99. Furthermore, within the CNR one should add the Hα absorbing dust cocoons associated to each one of the Paα-emitting blobs (Fig. 1).

3.3. Nuclear Colors, Dust, or Stellar Population?

Figure 4 shows the NIR color-magnitude diagram $(J - K_s)$ versus K_s for 0″.1 rebinned pixels in the central region of NGC 1241. The figure presents a color excess $E_N(J - K_s) \approx 0.2$ of the nucleus with respect to the CNR in a different manner (cf. Fig. 3). It is not possible to obtain a WTC92 model fitting of both the very red $(J - K_s)$ color excess and the very blue nuclear $(V - H)$. The reddening arrow in Figure 4 points to the same direction where the nuclear $(J - K_s)$ at the top of the CMD bends. Therefore, it suggests that dust may affect in a rather subtle way the nuclear $(J - K_s)$ without influencing $(V - H)$. Our solution to this rather tricky issue is that carbon stars are natural candidates to explain the infrared excess. Consideration of the LMC infrared CMD of Nikolaev & Weinberg (2000) leads us to propose these substantial contribution from carbon stars to the nuclear stellar population. Following a procedure similar to
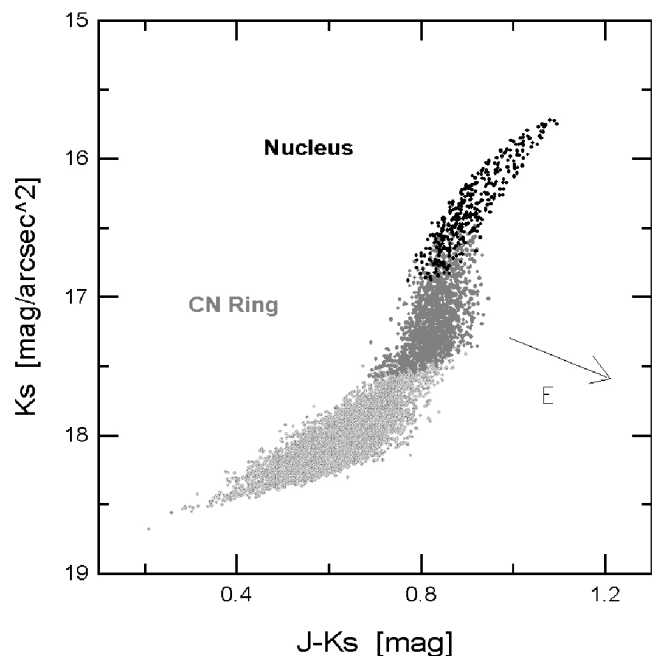

Fig. 4.—NIR color-magnitude plot for 0″.1 rebinned pixels. The radial positions corresponding to the nuclear region and the CNR and the reddening direction [representing $E(J - K_s) \approx 0.2$] have been noted.

that of Nikolaev & Weinberg (2000), we have used the 2MASS All-Sky Point Source Catalog Statistics Service facility[4] to obtain an integrated color-magnitude synthesis of the LMC bar, and we have compared it to the NGC 1241 nucleus.

The 2MASS service provides CMD diagrams and integrated light photometry in J, H, and K inside user selected circular regions. We choose five circular fields along the LMC bar and two foreground regions per bar field, one located 10° north and another 10° south of the bar. All regions and fields were selected with 30′ radius. Extractions from the 2MASS Point Source Catalog were performed. Figure 5 shows the CMD diagram corresponding to the center of the LMC bar and to the corresponding comparison field. Then, for each of the five regions the north and south foreground fields were averaged, and the mean brightness subtracted from the corresponding region to correct for foreground contamination. The final integrated surface magnitudes were obtained by flux-averaging the five background-corrected integrated surface magnitudes of the regions. The results were $\langle J \rangle = 20.38 \pm 0.07$ mag arcsec², $\langle H \rangle = 19.59 \pm 0.08$ mag arcsec², $\langle K \rangle = 19.38 \pm 0.07$ mag arcsec², and $\langle J - K \rangle = 1.00 \pm 0.10$ mag. The $\langle (J - K) \rangle$ color closely agrees with the color of the nucleus of NGC 1241. A similar color was obtained by Cole (2001) for the Sagittarius Dwarf galaxy, after correction for our Galaxy contamination.

4. FINAL REMARKS

We have discussed two dimensional photometry of the central 2 kpc of the Seyfert 2 galaxy NGC 1241, where a circumnuclear ring of star formation and the nucleus present peculiar colors when compared to the underlying disk. *HST* and Gemini imagery have been reduced to a uniform photometric system in order to allow the study of the photometric properties of these subsystems. While the dust arm produces the reddening of the CNR near side with respect to the CNR far side, we propose that an additional source of diffuse dust obscures uniformly the CNR, thus producing a global reddening of the CNR compared to the underlying disk. Inside the CNR, there are cocoons of dust associated to the Paα-emitting condensations.

Finally, the very red $(J - K_S)$ color of the nuclear region, together with the surprising transparency of this region in $(V - H)$, led us to propose a CMD for the nucleus similar to that of the LMC bar. C stars can in fact significantly redden the integrated colors at unresolved scales, a situation similar to that we are facing in the nuclear region of NGC 1241. Carbon stars
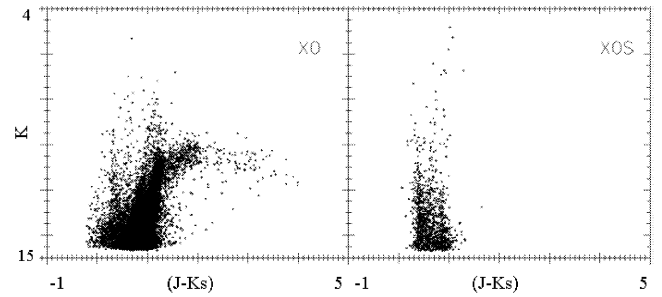
[4] See http://irsa.ipac.caltech.edu/applications/Stats.

Fig. 5.—CMD of the LMC bar center (*left*) and a Milky Way field (*right*) located 10° north of the bar.

and asymptotic giant branch (AGB) oxygen-rich stars evolve rapidly ($t < 3 \times 10^4$ yr) and eject considerable amounts of dust and gas with velocities low enough ($V_{gas} < 100$ km s^{-1}) to be trapped by the gravitational potential barrier of the central mass concentration ($M_{Kepler} \sim 10^9 M_\odot$, $r < 300$ pc). The 500 (6 $M_\odot$) C stars and 2.5×10^4 AGB O-rich stars (according to the LMC bar proportion) inside a radius of about 50 pc that are necessary to explain the nuclear colors would release material that, gravitationally bounded, could amount to between 10^{-2} and 10^{-1} $M_\odot$ yr^{-1} of fuel for the central engine. The intranucleus medium contamination may last during the lifetime of stars with masses $2 M_\odot < M_{C\,stars} < 6 M_\odot$. This scenario may also explain the systematic increase of the strength of the optical CN bands observed in the stellar populations of Seyfert 2 galaxy nuclei (e.g., Gu et al. 2001), and the significant contribution of intermediate-age stars to the optical continuum of low-luminosity active galactic nuclei (e.g., González-Delgado 2004).

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