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NGC 2403: A FLOCCULENT GALAXY WITH TWO PRINCIPAL CENTRES OF STAR FORMATION

John Beckman, Jordi Cepa, Mercedes Prieto, and Casiana Muñoz Tuñón

Instituto de Astrofísica de Canarias

RESUMEN. Hemos mapeado la galaxia espiral próxima floculenta NGC 2403 en las bandas visibles U, B y V, y en las bandas del infrarrojo cercano J, H y K, con una resolución espacial lineal de 900 pc. La galaxia, que no muestra una estructura espiral marcada en fotografias visibles (Tammann y Sandage, 1968) ni en la línea de 21 cm del HI (Wevers, 1984), parece tener dos centros actuales de formación estelar a gran escala, indicados por centros de flujo ultravioleta. Uno se encuentra en el núcleo, definido por el centro geométrico de la emisión HI, y el otro en aproximadamente 1.5 kpc de distancia radial desde el centro. La región de formación estelar más externa es la más intensa de las dos, y la más joven, y corresponde a un pico local en la densidad superficial de HI. Utilizamos los colores de las regiones de formación estelar y de la galaxia integrada para estimar, a primer orden, la distribución de poblacion estelar.

ABSTRACT. We have mapped the nearby flocculent spiral galaxy in the visible U, B and V bands, as well as in the near infrared J, H and K bands, with a linear resolution of 900 pc. The galaxy, which does not show marked spiral structure in visible photographs (Tammann and Sandage, 1968) nor in the 21 cm line of HI (Wevers, 1984) is found to have two principal current centres of large-scale star formation, signposted by centres of ultraviolet and blue flux. One is in the nucleus, defined by the geometrical centre of the HI emission, and the other at some 1.5 kpc radial distance away. The outer star-forming region is the more intense and the younger of the two, and corresponds to a local peak in the HI surface density. We use the colours of the star-forming regions and of the integrated galaxy to make a first order estimate of the stellar population distribution.

Key words: GALAXIES-SPIRAL — STARS-FORMATION

I. INTRODUCTION

The spiral galaxy NGC 2403 is classified as SAB (s) cd (de Vaucouleurs et al., 1976). This is somewhat fragmented, and the description of the galaxy as flocculent by Elmegreen (1981) gives a truer picture of its structure. In the revised Shapley-Ames Catalogue (Sandage and Tammann, 1981) it is described as Sc (s) III, which shows the difficulty of meaningful classification. Star formation appears to be proceeding at many points throughout the "disc" as shown by the large number of HII regions reported by Hodge and Kennicutt (1983) who observed 605 HII region complexes, whose distribution follows rather closely the HI surface density as mapped by Shostak et al. (1973) and by Wevers (1984). Other clear evidence for widespread star formation was provided by ultraviolet observations with the ANS satellite (Israel et al., 1985) which proved the presence of OB associations by observing strong ultraviolet excesses at points known to contain strong concentrations of HII regions. The angular resolution in this case was fairly coarse: some 2.5 arcminutes on a galaxy whose optical (Holmberg) radius is cited as 14.5x7.5 arcminutes (Wevers, 1984).

The only previously calibrated two-dimensional photometric studies of NGC 2403 were by Okamura, Yakase and Kodaira (1977) in the B and V bands and by Wevers (1984) in the U´ and F bands. The former authors draw attention to an apparent ring of "blueing", which shows up in the azimuthally averaged profile in B-V between 2 and 4 arcminutes from the centre of the galaxy, and lies somewhat inside the radius of maximum HI surface density described by Rogstad and Shostak (1973). However, Wevers (1984), using an angular resolution in HI of 45 arcseconds, showed that while there are indeed concentrations of HI peaks in the 2 to 4 arcminute range, the description of the sum as an annulus is not very meaningful, especially if dynamical conclusions are implied. The azimuthally averaged HI profile does indeed show a peak at 5 arcminutes from the centre, some 20% above the surrounding surface density; Wevers (1984) data do not, however, indicate any corresponding bump in the radial gradient of U´-F.

As part of a spectroscopy and mapping programme in the near infrared, designed to elucidate the relationship between stars and gas in the evolution of spirals, we mapped NGC 2403 in the J, H and K bands, following this up by U, B and V maps. For these tasks we had at our disposal the combined observing facilities of the Instituto de Astrofisica de Canarias. In this paper we present the results of a first analysis of these data, with its interesting light on the process of star formation in flocculent galaxies.

II. THE OBSERVATIONS

The visible (U, B, V) observations were taken with the "People´s" Photometer of the f/15 Cassegrain focus of the 1m Jacobus Kapteyn Telescope (JKT) of the Observatorio del Roque de los Muchachos. The measurements were made in a series of stepped rasters, with a photometric aperture of 28 arcseconds, and undersampled distances between individual points of 1 arcminute. The total field covered was 12 arcminutes in right ascension by 5 arcminutes in declination. Integration times of order 15 seconds per pixel gave integrated counts in the range $5x10^4$ on the nucleus, and mean values in the range $3x10^3$ across a scan, corresponding to photon noise limited signal to noise ratios of $\gtrsim$ 50. At the limits of the scans, after sky subtraction, counts were typically of order 100 in U, 200-300 in B and 500 in V. The photometer uses standard calibration stars to yield automatically the count rate per second in each band, taking into account atmospheric extinction and any dead time intrinsic to the observing technique. The data included here were obtained on the night 13/14 February 1985, on which night the extinction K_V above the observatory, measured via the Calsberg Automatic Transit Circle, was 0.14 mag airmass^{-1} . This was extrapolated to the other wavelength ranges, using the relation $K_B - K_V$ =0.11 mag airmass^{-1}, and $K_U - K_B$ =0.38 mag airmass^{-1} , values obtained from long-term measurements above the site.

The infrared maps were taken at the Cassegrain focus (f/13.5) of the 1.5m Sanchez Magro Telescope (SMT) at the Observatorio del Teide using a pumped liquid nitrogen-cooled InSb photoconductive detector. The filters were in the J, H and K bands centred at 1.3, 1.66 and 2.17 microns respectively, with half-widths 0.24, 0.26 and 0.37 microns respectively. The scans in this case were not stepped, but continuously driven in right ascension, across a scan length of 12.9 arcminutes. In this case the data were sampled along the scan with the "required" Wiener factor of half the resolution interval, i.e. at intervals of 13 arcseconds. Pairs of scans were separated by 1 arcminute in declination, and hence were significantly undersampled in this coordinate. Correction for extinction above the observatory site were made via measured mean extinction, i.e. K_J =0.2 mag airmass $K_H \approx K_K$ =0.1 mg airmass^{-1}

III. THE MAPS

Reduction of the isophotes to corrected apparent magnitude scales was performed using calibration stars as photometric standards, a procedure described in detail elsewhere (Cepa et al., 1986). Correction for extinction due to our own galaxy was obtained from the standard visual extinction law of de Vaucouleurs and Buta (1983), as a function of galactic co-ordinates l and b, and the empirical relationship of Johnson (1966) used to apply the extinction in all observed passbands. Internal extinction is less reliably computed, but we have evolved a method for this which is completely independent of the photometry.

This consists, as explained in a previous paper (Prieto et al., 1985) in using the measured surface density of hydrogen, summing the molecular and atomic forms, and an assumed uniform ratio of dust to gas, to derive the extinction two-dimensionally over the galaxy. We must make specific assumptions also about the distribution of stars and gas normal to the plane of the galaxy (see Prieto et al., 1985).

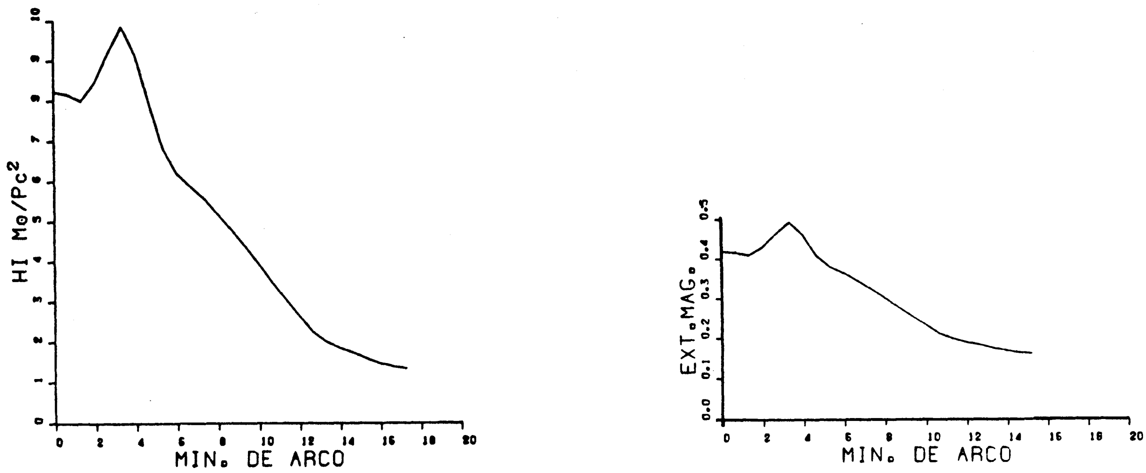

Fig. 1. Azimuthally averaged radial distribution of HI on the disc NGC 2403 and the inferred visual extinction, plotted against radius from the nucleus.

The azimuthally averaged extinction profile of the galaxy is shown in Fig. 1. The peak of just over 3 arcminutes from the nucleus undoubtedly takes in the effect of the strong concentration of dust associated with the strong emission peak away from the nuclear zone, which we examine in more detail below.

In Fig. 2 we show the maps in 6 bands, and in Table 1 the magnitudes of the isophotes superposed on the photograph of the galaxy.

TABLE 1. Magnitudes of the isophotes shown in the maps of Fig. 2

Filter	Lowest mag/arcsec	Interval mag/arcsec
U	19.71	0.5
B	20.60	0.5
V	19.96	0.4
J	18.14	0.4
H	18.85	0.4
K	17.81	0.4

The most striking feature of the U, B, V maps is the presence of a hot source to the northwest of the centre, because this shows up more strongly in U than in either B or V. Another intense source to the west and slightly south has been well identified as a field star (Sandage, 1984) and needs no further discussion. The nucleus itself shows up most strongly in B and V, although there is also a peak in U. The signal to noise ratios in the infrared maps are significantly inferior to those in the visible, and the H map in particular is not felt to be of great quantitative value. We will use only integrated infrared quantities for numerical deductions, although by inference the distributions in J and K are used deriving the population scheme.

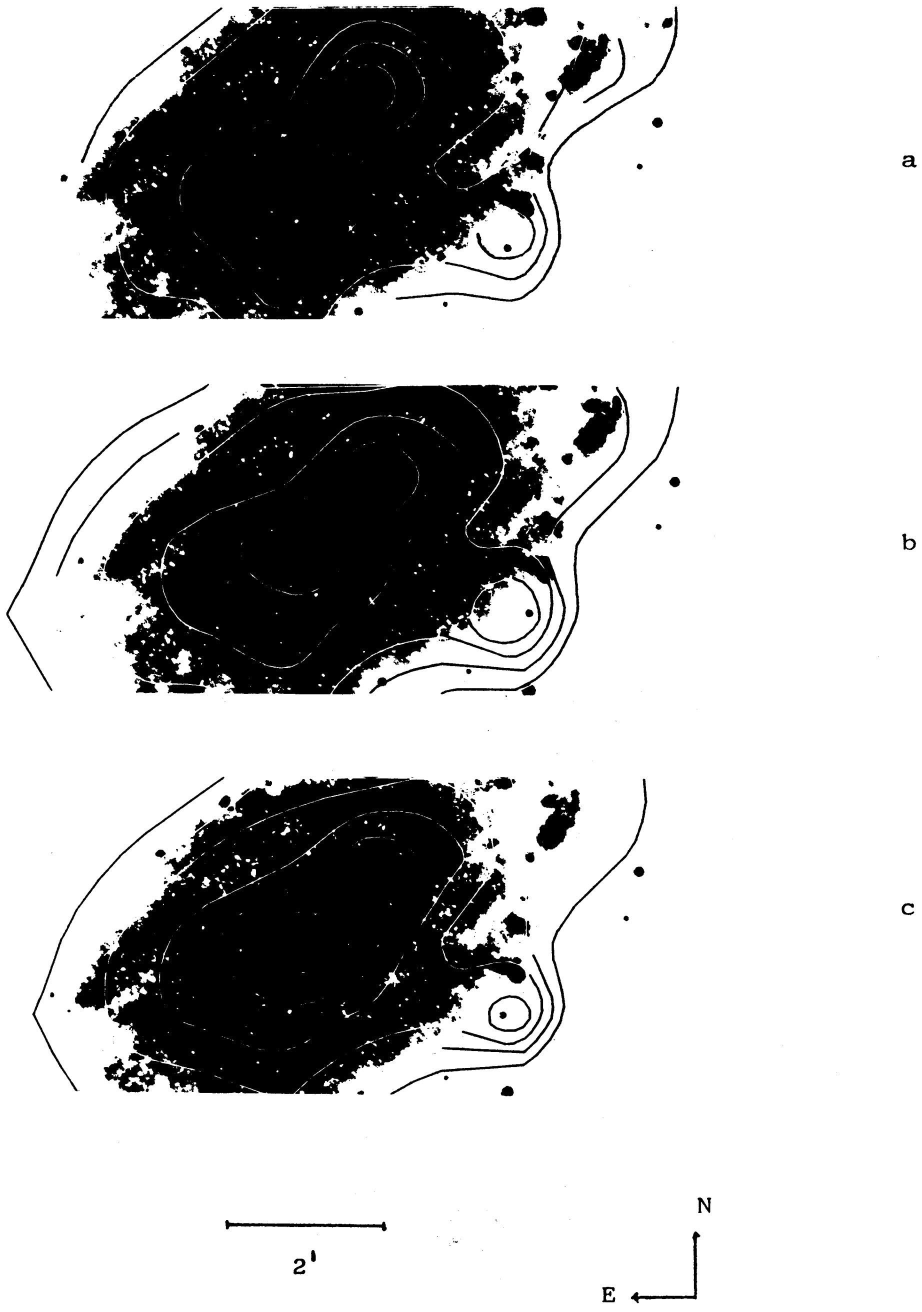

Fig. 2. Maps of NGC 2403. a, b and c represent the galaxy with the visible filters U, B and V respectively and d, e and F with the infrared filters J, H and K respectively. In Table 1 we give the minimum magnitude per arcsecond square and the intervals between isophotes for each filter.

Fig. 2. Map of NGC 2403 (continued).

V. STAR FORMING CENTRES

Combining a broad observational approach to star formation processes in flocculent spirals with the appearance of the two main centres of emission in NGC 2403 we can hypothesize that the latter represent groups of young stars which have formed (at least semi-) independently. These groups must be very luminous in order to appear as distinct sources, and must be very blue, because there is obvious dust in each, from the photographic images, yet the U and B bands have similar or greater luminosities than the V. The north-west (NW) peak has been associated with 2 HII regions (Grigor´eva, 1979; Hodge and Kennicutt, 1983), clear signs of star-forming complexes. Using simplifying assumptions we can estimate the flux in the two centres, starting with the NW peaks. For this peak, the major assumption is that the luminosity is dominated by O stars; this assumption can be checked for self-consistency and modified as necessary. The NW can be assigned, somewhat artificially, a diameter of 1 arcminute centred on the centre of symmetry of the brightest isophote in U, from which we derive the integrated apparent magnitudes, m , m , m of the sources, given in Table 2.

TABLE 2. Integrated apparent and absolute magnitudes, for the extended NW source in NGC 2403, and the numbers of 05 stars which would produce the observed absolute fluxes.

Magnitude	U	B	V
mapp	11.86	12.19	11.85
mapp (corr)	8.12	9.07	9.48
Mabs	-15.70	-15.37	-15.70
Mabs (corr)	-19.44	-18.49	-18.08
N (05)	$5x10^4$	$6x10^4$	$6x10^4$

The absolute magnitudes in each band are readily computed given the distance to NGC 2403 of 3.25 Mpc, a value which has been refined through much observation, as NGC 2403 has been adopted by Sandage as a primary distance standard.

From Table 2 we see that B-V is +0.34, which would correspond to a stellar type of late B. If we assume in view of the ultraviolet flux, that in fact the "mean" luminosity comes from 05 stars, we obtain a value for the colour excess of E(B-V)=0.79, and hence for the redenning of A_V =2.4 mag (Allen, 1973). Using mean extinction-colour curves for our own galaxy from Johnson (1966) we derive the U and B extinctions as A_U =3.74 mag, and A_B =3.12 mag respectively. These extinction values correct the magnitudes in each band, yielding B-V=-0.45, U-B=-0.95, which compare with the values for 05 stars of (B-V) =-0.45, (U-B) =-1.2 and for BO of (B-V) =-0.34, (U-B) =-1.05. Given the uncertainties in each step, and especially in the slope of the extinction curve of the unknown source, we can say for certain only that we are dealing with an OB association. With the simplification of using only 05 stars. we can compute the number required to give the observed fluxes in each band giving a reasonably self-consistent value of $5x10^4$ 05 stars in the source.

This is indeed a luminous object, but does not correspond to any intrinsically unlikely concentration of mass or luminosity. The total mass of these 05 stars would be $\sim 2.5x10^6$ $M_\odot$, and for a mass function of Salpeter type, where the numerical fall-off of stars as a function of mass goes as $M^{-1.35}$ we can estimate a total cluster mass in stellar form of $\sim 2x10^8$ $M_\odot$. A very rough extrapolation of gas to stars ratio by mass, using our knowledge of the starburst galaxy NGC 6946 (Muñoz Tuñon et al., 1986) places the total mass of the source as $M_s \simeq 10^7$ $M_\odot$. This is only a few percent at most of the mass of a galaxy, and as the source occupies a few percent of the observed volume, the figure is not untoward. The total luminosity of the object is $\sim 10^9$ $L_\odot$ which again makes a not "out of limit" contribution to the luminosity of the galaxy. The luminosity density in the source is 10 $L_\odot$ pc^{-3} , asuming a disc thickness of 400 pc, which is an order of magnitude higher than that in the solar neighbourhood and the surface brightness is 10^3 $L_\odot$ pc^{-2} .

We can analyze the central, near-nuclear source in a similar way. In Table 3 we give the integrated magnitudes of this source within the central 1 arcminute radius for each band.

TABLE 3. U,B, V magnitudes for the central source of NGC 2403, with the number of B5 stars which would produce the corrected absolute fluxes.

Magnitude	U	B	V
Mapp	12.04	11.84	11.46
Mapp (corr)	8.94	9.07	9.39
Mabs	-15.52	-15.72	-16.10
Mabs (corr)	-18.82	-18.49	-18.17
N(B5)	7.5×10^{6}	9.2×10^{6}	8.9×10^{6}

Although the magnitudes in the three bands are of similar order to those in the NW source, the colours are significantly different. Using the same approach as in the other source, i.e. a self-consistent fit between the de-redenned colours and a dominant spectral type, we obtain a colour excess E(B-V)=0.7 mag and corresponding extinction A_V =2.07, A_B =2.77, A_U =3.30 mag. The corrected apparent and absolute magnitudes are listed in Table 3. The redenning and extinction corrections imply a best fit spectral type of B5, and one can compute seperately the number of B5 stars N(B5) corresponding to the absolute magnitude in each band. Given the consistency of the numbers, one can estimate 8×10^{6} such stars, with a total mass of 1.5×10^{9} $M_{\odot}$. The total stellar mass in the source would then be 3×10^{8} $M_{\odot}$, and the total mass of order 1.5×10^{9} $M_{\odot}$. The mass of this source is close to that of the NW source, even though the stellar composition is different. The principal difference between the two is that star formation in the NW source is occurring some 10^{7} years later than that in the nuclear zone.

V. THE INTEGRATED POPULATION OF THE GALAXY

It is of interest to consider the galaxy as a whole, comparing its integrated U, B, and V magnitudes with those of the star-forming centres it contains. We place an arbitrary radius of 8 arcminutes for integration purposes, estimating that more than 75% of the flux in each of the 3 visible bands lies within that radius. In Table 4 we list the magnitudes of the galaxy in each band.

TABLE 4. Integrated magnitudes for the portion of NGC 2403 within 8' of the nucleus.

Magnitude	U	B	V
Mapp	8.5	9.2	8.69
Mapp (corr)	7.9	8.7	8.4
Mabs (corr)	-19.65	-18.85	-19.15

The extinction correction in this case could not be estimated correctly from these measurements themselves, as clearly the extinction and the population vary from point to point in the galaxy. Instead we used the relation between the extinction A and the HI surface density (Wevers, 1984), viz. $A_V = 5.2\times10^{-2}\ \sigma_{HI}$ Mag $M_{\odot}^{-1}$ pc^{-2} together with the relations A_B =1.32 A_V ; A_U =1.58 A_V (Johnson, 1966). The values for U-B=-0.8 and B-V=+0.3 imply clearly that we are observing more than one component of stellar population. The simplest assumption for a system where star formation is continuing but where there is an underlying older population is to assume that O stars dominate the U band, and that K giants, which are the evolved successors to previous A and early F main sequence stars dominate the V band. It is clear that such a twin-peaked population cannot be a true representation of the distributon, but in NGC 2403 it is surprising how closely the U, B and V bands can be fitted by basically these two stellar types, with a small contribution from B5.

In Table 5 we list the absolute luminosities of NGC 2403 and of the U, B and V contributions of the three types: O5 and B V main sequence stars, and K0 giants.

TABLE 5. U, B, and V luminosity distribution (the luminosity of a zero magnitude object is the standard unit in each band) for NGC 2403 and the selected stellar component types.

Object	Luminosities L_U (L_{U_0} =1)	L_B (L_{B_0} =1)	L_V (L_{V_0} =1)
Central 8′ of disc of NGC 2403	8.2×10^{7}	3.9×10^{7}	4.6×10^{7}
O5V	1.15×10^{3}	3.8×10^{2}	2.5×10^{2}
B5V	4.5	2.68	2.30
KOIII	7.8×10^{-2}	1.8×10^{-1}	4.7×10^{-1}

We obtain a satisfactory solution to the observed fluxes from the mixture of stars given in Table 6.

TABLE 6. Recipe for stellar mixture to reproduce the observed U, B and V integrated fluxes in NGC 2402.

Stellar type	Number	Flux Contributions U	B	V
O5V	5.5×10^{4}	5.7×10^{7}	1.8×10^{7}	1.2×10^{7}
B5V	8×10^{6}	2.5×10^{7}	1.3×10^{7}	1.2×10^{7}
KOIII	6.5×10^{7}	0.4×10^{7}	0.9×10^{7}	2.3×10^{7}
Total flux		8.6×10^{7}	4.1×10^{7}	4.7×10^{7}
Galaxy		8.2×10^{7}	3.9×10^{7}	4.6×10^{7}

The fact that the synthesized fluxes are a little high can be attributed to our failure to include any contributions from H in the extinction formula (due to an absence of published data), so that the estimated galaxy fluxes will be lower limits.

We can draw some global conclusions from these results: firstly essentially all of the O5 stars in the galaxy are contained in the young NW region, because the total O5 contribution from the galaxy is more or less equal to the O5 flux estimated from the NW complex. Ths is a satisfactory conclusion because we see no evidence for any other major young system. Similarly most of the B5 objects in the galaxy are found in the star-forming complexes. In the V band the galaxy light is somewhat dominated by the evolved stars whch is again expected from the disc of a typical spiral, outside the spiral arms. We derive a picture of star-bursts occuring in NGC 2403 at points not obviously connected by morphological features. Only a careful look at the gas velocities would tell us whether or not there was any strong physical link between them.

VI. INFRARED FLUXES

The integrated absolute magnitudes in J and K, which are reliable to within 0.2 magnitudes, are -21.0 and -22.15 respectively when corrected for internal extinction via the HI surface density. Tabulating the contributions via their fluxes we have:

TABLE 7. Comparison of observed J and K fluxes for NGC 2403 with those predicted from the population mix in Table 6.

Object	Luminosity L_J ($L_{J_\odot}$ =1)	L_K ($L_{K_\odot}$ =1)
Central 8′ of disc of NGC 2403	2.5×10^8	7.2×10^8
O5 (5.5×10^4)	6.0×10^6	4.4×10^6
B5V (8×10^6)	1.15×10^7	1.0×10^7
KOIII (6.5×10^7)	1.4×10^8	2.4×10^8

A glance at Table 7 shows that the O and B stars as expected, do not contribute significantly in J or K; somewhat more suprisingly the KO giants do not supply adequate luminosities in these bands. The differences unaccounted for amount to -20.1 in J magnitude and -20.95 in K, which corresponds to J-K of 0.85. The "infrared population" must therefore be later than KO, for which J-K is 0.6. Bearing in mind the errors in the J and K magnitudes we cannot use the value of 0.85 to specify the underlying population, but we can use quantitative arguments to delimit its nature. It is not possible to obtain the extra 4.5×10^8 $L_{K_\odot}$ from K5 objects (dwarfs or giants) because these would make a contribution in the V band too great to be consistent with the previous analysis. In the case of K5III, for example, the V contribution would be 3×10^7 $L_{V_\odot}$; and the K5 objects would nearly double the predicted luminosity. A trial with later-type objects meets with more success. The addition of 3.5×10^{10} Mo dwarfs would supply the required J and K luminosities, with adding 9×10^6 $L_{V_\odot}$ in V which is an apparent excess of some 15% or 0.15 mags.; within the limits of error of the corrected V band observation; the B and U contributions would be 5 and 10 times less significant respectively. This number of MO dwarfs will contribute ~ 10 $M_\odot$ to the galaxy a figure in no way out of line with known masses of galaxies and their sub-components.

VII. CONCLUSIONS

This paper is a practical illustration of mapping for the analysis of stellar population in galaxies. We have been able to dissect NGC 2403 into two major star-forming regions, and to show that one, the NW region, is very young, while the nuclear region is more than 10^7 years old (all times internal to NGC 2403 neglecting its light - travel distance of 10^7 light years). We also show the utility of the infrared bands in separating the underlying older population from younger star-forming regions. These kinds of studies, especially incorporating improved angular resolution will be valuable in separating arm from interarm populations in the discs of spirals. Although the arm-interarm intensity contrast is low in V and B and dust-obscured in U, the infrared measurements allow the underlying older population to be assessed and subtracted out, leaving the new stellar regions for easier study.

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J. Beckman, J. Cepa, M. Prieto y C. Muñoz Tuñón: Instituto de Astrofísica de Canarias, 38071 La Laguna, Tenerife, Islas Canarias, Spain.