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ON THE ORIGIN OF THE ULTRAVIOLET CONTINUUM IN SEYFERT 2 GALAXIES

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ABSTRACT

High-resolution *Hubble Space Telescope* ultraviolet images of the Seyfert 2 galaxies NGC 1667, NGC 3982, NGC 5427, and NGC 5953, previously known to have circumnuclear star-forming rings, are presented.

The UV images of all four Seyfert 2 galaxies show the presence of several compact UV-bright knots at distances of ∼0.7–2 kpc from the nucleus and associated to the circumnuclear star-forming ring. The optically bright Seyfert 2 nucleus is barely detected in the UV.

The UV images provide the first direct empirical evidence that the UV flux emitted by galaxies having a Seyfert 2–type nucleus surrounded by a circumnuclear star-forming ring is dominated by radiation coming from clusters of young hot stars distributed along the star-forming ring. The contribution of the Seyfert 2 nucleus amounts to ∼1%–10% of the observed UV flux in these four galaxies.

If circumnuclear star-forming rings of 2–3 kpc in diameter, or smaller, are a common feature of Seyfert 2 galaxies, we conclude that (*a*) the observed UV flux in Seyfert 2 galaxies is not dominated by the radiation from the nuclear ionizing source and (*b*) the observed UV flux is dominated by emission from clusters of young hot stars located in circumnuclear star-forming regions.

Whatever the nature of the nuclear ionizing source in these Seyfert 2 galaxies, this must be obscured. The UV and Hα luminosities associated to the Seyfert 2 nucleus in these galaxies are consistent with the scenario of the nuclear ionizing source being an obscured power-law ionizing source or a young (2–4 Myr) obscured high-metallicity ($\geq Z_{\odot}$) nuclear starburst.

Subject headings: — galaxies: active — galaxies: nuclei — galaxies: spiral — galaxies: starburst — galaxies: star clusters — ultraviolet: galaxies

1. INTRODUCTION

The question of the origin and nature of the ultraviolet continuum in Seyfert 2 galaxies has always been a matter of debate and has recently received much attention (Cid-Fernandes & Terlevich 1995; Heckman et al. 1995, 1997). Already back in 1982, Lawrence & Elvis (1982) suggested, on the basis of the ratio of hard to soft X-ray flux in Seyfert galaxies, that Seyfert 2 galaxies were in fact obscured Seyfert 1 galaxies. However, it was not until the detection of broad polarized optical emission lines in the Seyfert 2 galaxy NGC 1068 (Antonucci & Miller 1985) that the unified scenario of Seyfert 2 galaxies as obscured Seyfert 1 galaxies started to be accepted as a working hypothesis. The presence of a featureless ultraviolet continuum in Seyfert 2 galaxies was considered to be further evidence for this unifying scenario, the UV continuum being radiation scattered in our line of sight from the obscured nucleus. However, this view has been challenged in the past few years. On the basis of multifrequency studies of a large sample of Seyfert galaxies, Mas-Hesse et al. (1994, 1995) concluded that the average excess of UV emission in Seyfert 2 galaxies with respect to Seyfert 1 galaxies could be due to the contribution of star-forming regions close to the nucleus. Also, Heckman et al. (1995) showed that the UV template of Seyfert 2 galaxies, formed from the *IUE* spectra of 20 bright Seyfert 2 galaxies, is not compatible with the scenario of radiation scattered from the obscured nucleus but rather with the hypothesis of the UV light being dominated by a reddened starburst. Moreover, Heckman et al. (1997) have recently shown that the ultraviolet to near-infrared continuum in the bright Seyfert 2 galaxy Mrk 477 is dominated by a dusty starburst.

What is the origin of the UV continuum in Seyfert 2 galaxies? If stars play a significant role, where are they located? Are they nuclear starbursts, i.e., located in the inner 10–20 pc, or are they more likely to be distributed in circumnuclear star-forming knots or rings, i.e., situated at distances of several hundred parsecs from the nucleus? What fraction of the Seyfert 2 galaxies have circumnuclear star-forming structures?

To further investigate these fundamental questions, we present in this Letter new results of a *Hubble Space Telescope* (*HST*) ultraviolet imaging program. WFPC2 F218W images of four low-redshift spiral galaxies previously known to have a Seyfert 2 nucleus surrounded by a circumnuclear star-forming ring are presented. We explain the results and briefly discuss their implications for the origin of the ultraviolet continuum in Seyfert 2 galaxies and for the scenario of Seyfert 2 galaxies as obscured Seyfert 1 galaxies.

NGC 1667 is a barred spiral galaxy. *IUE* observations show Si IV and CIV absorption lines as direct evidence of massive stars (Thuan 1984), while the radio emission is diffuse and not dominated by the active galactic nucleus (AGN; Ulvestad & Wilson 1989). Ground-based Hα images (González Delgado et al. 1997) and spectroscopy (Radovich & Rafanelli 1996) reveal the presence of a bright Seyfert 2 nucleus surrounded by luminous star-forming regions.

NGC 3982 is a barred spiral classified as Seyfert 2 (González

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TABLE 1
ADOPTED PROPERTIES FOR THE SAMPLE OF SEYFERT 2 GALAXIES

Galaxy (1)	Morphology (2)	i (deg) (3)	$A_g(B)$ (mag) (4)	V_{sys} (km s^{-1}) (5)	D (Mpc) (6)	L_B ($L_\odot$) (7)	L_{FIR} ($L_\odot$) (8)	L_{IR} ($L_\odot$) (9)
NGC 1068	Sb	29	0.06	1176	14.4	10.75	10.77	11.29
NGC 1667	SAB(r)c	36	0.24	4459	59.5	10.78	10.62	10.88
NGC 3982	SAB(r)b	26	0.00	1208	17.0	9.97	9.59	9.86
NGC 5427	Sc	17	0.07	2483	38.1	10.57	10.22	10.47
NGC 5953	Sa	43	0.11	2147	33.0	10.03	10.31	10.57

NOTE.—Col. (2): Morphological type from RC3, from de Vaucouleurs et al. 1991; col. (3): inclination of the galaxy; col. (4): Galactic extinction; col. (5): system velocity; col. (6): distance; col. (7): absolute luminosity in the blue band; col. (8): far-IR luminosity computed from the 60 and 100 μm *IRAS* fluxes of Fullmer & Lonsdale 1989; col. (9): IR luminosity computed with all four *IRAS* fluxes, from Perault 1987. Data for cols. (3)–(7) come from Tully 1988, except for NGC 1667, where the properties are compiled in González Delgado et al. 1997. The blue luminosity for NGC 1667 has been obtained by converting the apparent magnitude listed in RC3 ($m_B =$ 12.41) to luminosity with Tully's 1988 expression. NGC 1068 is included in the table for comparison.

Delgado, unpublished; Phillips, Charles, & Baldwin 1983) that, however, presents a UV spectrum with absorption lines (Kinney et al. 1993). Ground-based Hα and [O III] images (González Delgado et al. 1997) clearly show the presence of an unresolved high-excitation nucleus surrounded by a ring of star-forming regions, some of them also detected in [O III] light.

NGC 5427 is an Sc spiral galaxy in interaction with NGC 5426. The Hα image (González Delgado et al. 1997) clearly shows a circumnuclear ring of star-forming regions, while the [O III] emission is dominated by the bright Seyfert 2 nucleus (González Delgado et al. 1997).

NGC 5953 is an Sa spiral galaxy with a Seyfert 2 nucleus that seems to be interacting with its companion galaxy NGC 5954. The circumnuclear star-forming regions have a high metallicity (~3 $Z_\odot$), and the ionized gas in a region northeast of the nucleus shows indications of a mixture of high- and low-excitation conditions, i.e., of ionization by hot stars and an AGN (González Delgado & Pérez 1996).

The adopted properties of the galaxies in the sample can be found in Table 1. Data for the prototype Seyfert 2 galaxy NGC 1068 are also included in this table for reference.

2. OBSERVATIONS AND DATA REDUCTION

Ultraviolet images of all four galaxies were obtained with the *HST* WFPC2 with WF3 and the F218W filter (width of 388 Å). The images have a total integration time of 20 minutes, split in two integrations of 10 minutes each. The individual images were recalibrated with the optimum dark frames, and the final images were created by combining the two individual images, after removal of cosmic rays.

Red leaks do not affect measurements with the F218W filter. The overall system sensitivity for this filter drops rapidly and at 4500 Å is 10^{-4} the sensitivity at 2200 Å. For O-, B-, and A-type stars, the red leak (contribution longward of 2800 Å) represents less than 1% of the measured flux, and even for solar analogs the red leaks represent ~8% of the measured flux (Biretta et al. 1996). The decline in the UV sensitivity of the WFPC2 as a function of time (Biretta et al. 1996 and references therein) has been accounted for, and appropriate corrections are included in the zero point of the absolute photometry. The fluxes are corrected for Galactic reddening (see Table 1) but not for internal reddening. The UV fluxes and luminosities listed in this Letter should therefore be considered a lower limit.

3. RESULTS AND DISCUSSION

3.1. *Morphology of the Central Regions of Seyfert 2 Galaxies in the Ultraviolet*

All four galaxies in the sample show a similar morphology in the ultraviolet characterized by a faint nucleus and a few or several compact circumnuclear UV-emitting knots, distributed in a ringlike structure (see Figs. 1 and 2 [Pl. 6 and 7]). The circumnuclear UV-emitting regions have overall linear diameters ranging from 1.4 kpc (NGC 5953) to 4 kpc (NGC 1667) and are associated to bright star-forming rings detected in ground-based Hα images (see Figs. 1 and 2; González Delgado et al. 1997). The size, UV, and Hα luminosities of the circumnuclear star-forming rings in these four Seyfert 2 galaxies are similar to those detected in the prototype Seyfert 2 galaxy NGC 1068 (see Table 2).

The Seyfert 2 nucleus, clearly seen in the Hα images for all four galaxies as the brightest knot in the central region, is barely detected in the UV images (see Figs. 1 and 2). This comes as a surprise, as all four galaxies have an inclination close to the plane of the sky, i.e., close to face-on, and similar to that of NGC 1068 (see Table 1 for specific inclination angles). Therefore, bright UV nuclei were naively expected to show up in the UV images. Moreover, in our sample of four galaxies, the brightest UV nucleus is detected in NGC 5953, which has the highest inclination of all four galaxies (Table 1). These results suggest that the detection of a bright UV nucleus in Seyfert 2 galaxies does not necessarily correlate with the inclination of the host galaxy but rather with the local tridimensional distribution of gas and/or dust (dust lanes, molecular gas) surrounding the core of the galaxy.

3.2. *The Source of the Ultraviolet Continuum in Seyfert 2 Galaxies*

The combined UV luminosity of the Seyfert 2 nucleus plus bright compact circumnuclear star-forming knots is in the log L_{UV} = 38.6–39.7 ergs s^{-1} Å^{-1} luminosity range for the galaxies in this sample (see Table 2). The UV luminosity in all four galaxies is dominated by the circumnuclear star-forming ring, accounting for 90%–99% of the observed UV luminosity. The UV luminosity associated to the Seyfert 2 nucleus contributes to only 1%–10% of the observed UV luminosity (see Table 2). Although the faint UV flux of the individual UV knots prevents us from doing high spatial resolution UV spectroscopy, the UV emission in the ring is most likely coming from

TABLE 2

OBSERVED UV AND Hα+[N II] LUMINOSITIES FOR THE SAMPLE OF SEYFERT 2 GALAXIES

Galaxy (1)	Diameter (kpc) (2)	log L_{UV} (core) (ergs s^{-1} Å^{-1}) (3)	log L_{UV} (total) (ergs s^{-1} Å^{-1}) (4)	log $L_{H\alpha + [N II]}$ (core) (ergs s^{-1}) (5)	log $L_{H\alpha + [N II]}$ (total) (ergs s^{-1}) (6)
NGC 1068	3.1	38.86	39.21	41.65	41.79
NGC 1667	4.0	37.95	39.70	40.33	41.60
NGC 3982[a]	2.5	36.55	38.58	…	…
NGC 5427	2.1	37.59	38.95	39.72	40.52
NGC 5953	1.4	37.83	38.82	40.60	41.32

NOTE.—Col. (2): Diameter of the circumnuclear star-forming rings; cols. (3) and (4): observed UV absolute luminosity after correction for extinction in the Galaxy. L_{UV}(core) is the luminosity within a radius of 0$''$.5 centered in the nucleus, while L_{UV}(total) represents the integrated luminosity emitted by the core and the bright compact knots in the circumnuclear regions; cols. (5) and (6): observed Hα luminosity (no correction for internal reddening has been applied). NGC 1068 is included in the table for comparison. UV luminosities for NGC 1068 were converted from fluxes of Neff et al. 1994 and are given at a wavelength of 2490 Å. The quoted UV core luminosity for NGC 1068 was obtained for an aperture of 8$''$, from Neff et al. 1994.

[a] No absolute photometry is available for NGC 3982. The contribution of the core to the total Hα+[N II] luminosity is 4%.

clusters of young (4–5 Myr) hot stars as in the circumnuclear star-forming ring of NGC 3351 (Colina et al. 1997).

By contrast, the integrated observed UV luminosity of NGC 1068, the prototype of Seyfert 2 galaxies, corresponds to log L_{UV} = 39.21 ergs s^{-1} Å^{-1}, but the nuclear region (300 pc in radius; Neff et al. 1994) contributes to 45% of this value (see Table 2). However, additional UV measurements of the NGC 1068 nucleus show that the UV continuum measured through the *HST* Faint Object Spectrograph 0$''$.3 aperture (i.e., ~20 pc) is 7 times fainter than the UV flux measured by the Hopkins Ultraviolet Telescope with larger apertures (Kriss et al. 1993). It is still not clear whether star-forming regions exist at distances of about ~200 pc, or closer, from the core of NGC 1068, as in NGC 4303 (Colina et al. 1997).

These results provide the first direct empirical evidence that the UV continuum in at least a fraction of Seyfert 2 galaxies, those with surrounding circumnuclear star-forming rings, is dominated by radiation coming from young hot stars. Also, these stars are not located in the core of the galaxy, i.e., in the inner ~10–20 pc, but rather they are associated to circumnuclear star-forming rings at typical distances of a few or several hundred parsecs to 1–2 kpc from the core of the galaxy. Recent UV images of the low-redshift LINER-type galaxy NGC 4303 also support this conclusion. The *HST* UV image of NGC 4303 shows a very compact star-forming spiral structure located at distances of about 200 pc from the core of the galaxy and contributing 84% of the UV luminosity (Colina et al. 1997).

What fraction of Seyfert 2 galaxies have circumnuclear star-forming rings contributing to, and even dominating, the observed UV continuum?

Several recent studies indicate that circumnuclear star-forming regions in Seyfert 2 galaxies are more common than previously thought and that they could contribute, and even dominate, the UV flux in these types of galaxies. On the basis of a recent Hα survey of Seyfert galaxies and LINERs, González-Delgado et al. (1997) conclude that 30% of the Seyfert 2 galaxies have circumnuclear star-forming regions similar to those present in our sample galaxies, i.e., located at distances of ~0.5–2 kpc from the nucleus and resolved from the ground-based observatories for low-redshift galaxies. A multifrequency study of a large sample of Seyfert galaxies allowed Mas-Hesse et al. (1994, 1995) to conclude that the average excess of UV emission in Seyfert 2 galaxies relative to Seyfert 1 galaxies could be due to a contribution by circumnuclear star-forming regions. Reanalysis of the *IUE* spectra of 20 of the brightest Seyfert 2 galaxies favors the scenario that the UV continuum in these galaxies is in general dominated by a reddened starburst (Heckman et al. 1995).

If UV-bright circumnuclear star-forming rings, as those detected in our sample galaxies, are a common characteristic of Seyfert 2 galaxies, the large *IUE* aperture (10$''$ × 20$''$, equivalent to a linear size of 1.2 × 2.4 kpc or more, for distances of 25 Mpc or more) would include both the Seyfert 2 nucleus and the circumnuclear star-forming rings in most cases.

In summary, the results presented in this Letter support the conclusions of Mas-Hesse et al. (1994, 1995) and Heckman et al. (1995) and give the first direct evidence that in Seyfert 2 galaxies surrounded by star-forming regions, the observed UV flux is dominated by the emission associated to the star-forming regions. *HST* UV imaging of a complete sample of low-redshift Seyfert 2 galaxies is needed to investigate the UV properties of these galaxies, in particular (1) what fraction of the entire population of Seyfert 2 galaxies has a UV flux dominated by UV-bright star-forming knots and (2) whether these star-forming knots are located in the nuclear (inner few parsecs) or

TABLE 3

NUCLEAR IONIZING SOURCE: UV LUMINOSITIES FOR POWER LAWS AND STARBURSTS

Galaxy (1)	log $L^{core}_{H\alpha}$ (ergs s^{-1}) (2)	log L^{core}_{UV} (ergs s^{-1} Å^{-1}) (3)	log $L^{\alpha 1}_{UV}$ (ergs s^{-1} Å^{-1}) (4)	log $L^{\alpha 2}_{UV}$ (ergs s^{-1} Å^{-1}) (5)	log $L^{Z_\odot}_{UV}$ (2 Myr) (ergs s^{-1} Å^{-1}) (6)	log $L^{Z_\odot}_{UV}$ (4 Myr) (ergs s^{-1} Å^{-1}) (7)	log $L^{2.5\ Z_\odot}_{UV}$ (2 Myr) (ergs s^{-1} Å^{-1}) (8)	log $L^{2.5\ Z_\odot}_{UV}$ (4 Myr) (ergs s^{-1} Å^{-1}) (9)
NGC 1667 ……	40.47	37.95	38.33	39.01	38.51	38.92	39.05	39.25
NGC 5427 ……	39.75	37.59	37.61	38.29	37.79	38.20	38.33	38.53
NGC 5953 ……	41.03	37.83	38.89	39.57	39.07	39.48	39.61	39.81

NOTE.—Col. (2): Hα luminosity corrected for the contribution of [N II] and internal reddening; col. (3): observed core UV luminosity; cols. (4) and (5): predicted UV luminosity at 2200 Å if the Hα-emitting gas is ionized by a power-law ($F_\nu \propto \nu^{-\alpha}$) ionizing source with spectral indices of α = 1 and 2, respectively; cols. (6)–(9): predicted UV luminosities at 2200 Å if the Hα-emitting gas is ionized by a high-metallicity ($Z_\odot$ and 2.5 $Z_\odot$) starburst 2 Myr and 4 Myr old characterized by a Salpeter initial mass function with stellar mass limits of 0.8 and 100 $M_\odot$; see García-Vargas et al. 1995.

circumnuclear regions (inner several hundred parsecs) of the galaxies.

3.3. *Seyfert 2 Nucleus: Obscured Seyfert 1 or Young Stellar Cluster?*

The question of whether nuclear starbursts and AGNs are connected has been tackled by some authors suggesting that the AGN could be the final stage in the evolution of a nuclear starburst (Weedman 1983; Shapiro & Teukolsky 1985). These models predict that a central cluster of stars would evolve, collapse, and ultimately generate a black hole and an AGN. Other authors (Terlevich et al. 1992, 1994) suggest that different types of AGNs are in fact manifestations of different phases in the evolution of a star cluster located in the high-density, high-metallicity environment present in the core of early-type spiral galaxies.

Even if the Seyfert 2 nucleus detected in our UV images does not significantly contribute to the integrated UV luminosity, the question of the nature of the ionizing source associated to the Seyfert 2 nucleus is very important and still remains open. Is this ionizing source an obscured nonthermal source, i.e., an obscured Seyfert 1, or is it a nuclear high-metallicity stellar cluster?

To further investigate the nature of the nuclear ionizing source, the predicted ultraviolet luminosity has been computed assuming the nuclear Hα-emitting gas ($\log L_{H_\alpha}^{\rm core}$ in Table 3) is entirely ionized by (*a*) an isotropic power-law ($F_\nu \propto \nu^{-\alpha}$) ionization source and (*b*) a young high-metallicity stellar cluster. The results of these models are compared with the observed core UV luminosity in Table 3.

The Hα luminosities are consistent with either a moderately reddened [A(2200 Å) $\sim$ 0.05–2.5 mag] ν^{-1} power-law source or a moderately reddened [A(2200 Å) $\sim$ 0.5–3 mag] young (2 Myr) solar metallicity stellar cluster (see Table 3). If the slope of the power law is steeper or the age and metallicity of the stellar cluster are increased, the amount of extinction required to explain the difference between the predicted and observed UV luminosities will increase to A(2200 Å) $\sim$ 2–5 mag (see Table 3).

The extinction in the nuclear Hα-emitting gas, as derived from the Balmer lines, ranges from $E(B-V) = 0.4$ for NGC 5427 (González Delgado, unpublished) to 0.70 for NGC 1667 (Radovich & Rafanelli 1996) and 0.81 for NGC 5953 (González Delgado & Pérez 1996). If the nuclear ionizing source is obscured and the extinction curve derived for starbursts is considered (Calzetti 1997), the obscuration in the UV would amount to about 2.5–5 mag, consistent with the upper values derived above.

The obscuration of the UV nuclear source could also be consistent with the predictions of the unified model of AGNs. According to this scenario, the UV continuum would be completely blocked by the circumnuclear torus, so that we would detect only the contribution reflected by the warm gas located along the torus axes. The efficiency of this reflection is only a few percent, consistent with the results above. Furthermore, the Hα-emitting regions detected in the optical ground-based images could be ionized by the hard UV continuum escaping as well along the torus axes, forming ionization cones like the ones detected in other Seyfert 2 galaxies. Higher resolution Hα and [O III] observations with *HST* would be needed to definitely identify these cones in our sample's galaxies.

In summary, the nuclear Hα and UV luminosities measured in these four Seyfert 2 galaxies are consistent with ionization by either a reddened AGN-type power law or a reddened young stellar cluster.

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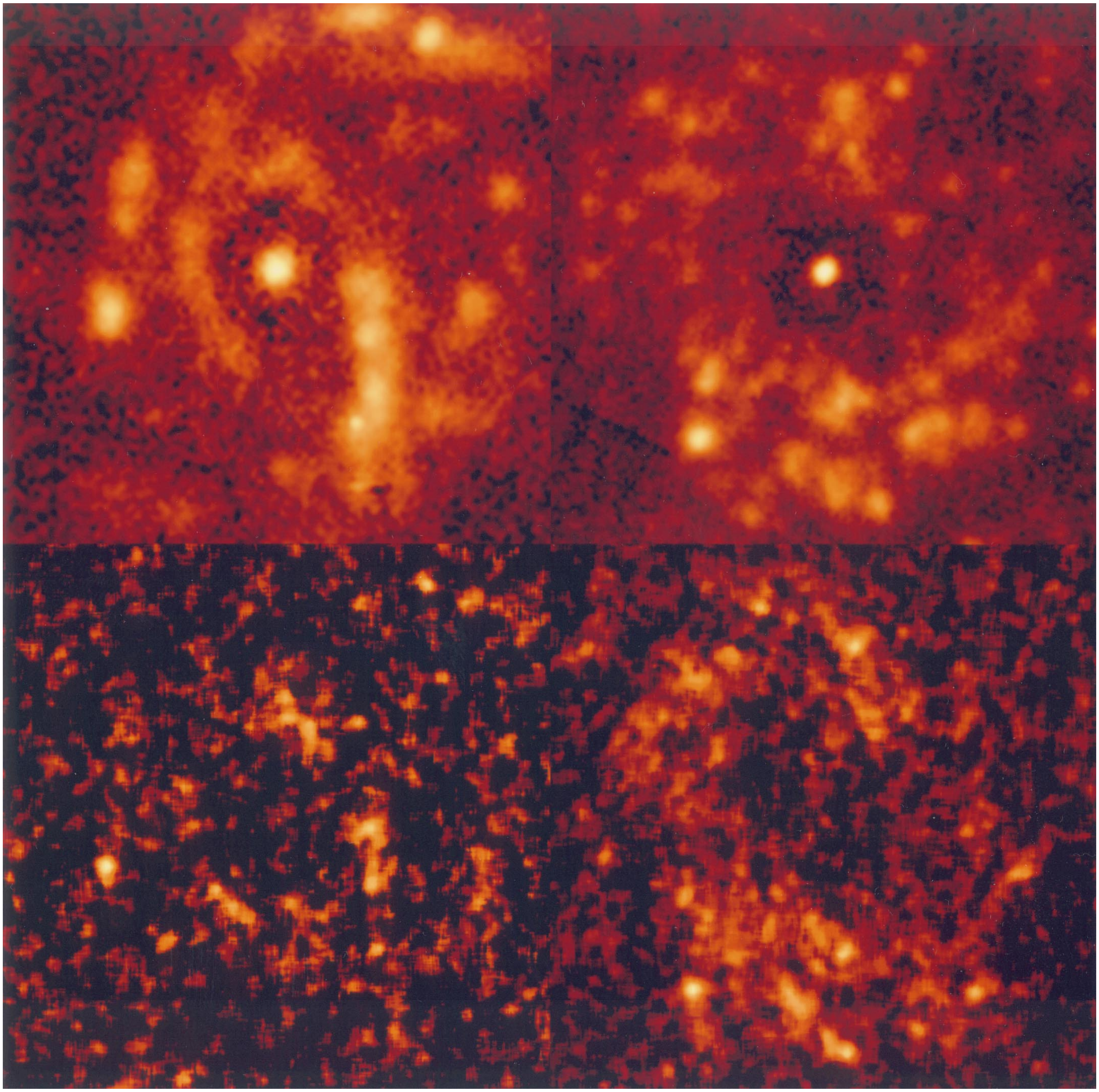

FIG. 1.—Composite image showing the Hα images of NGC 1667 (*top left*) and NGC 3982 (*top right*) and the filtered WFPC2 ultraviolet images (NGC 1667: *bottom left*; NGC 3982: *bottom right*). The images are oriented with north up and east to the left. Each Hα and UV image is 40″ on a side. Details regarding the Hα images can be found in González Delgado et al. (1997) The original WFPC2 ultraviolet images have been filtered with a median filter of 9 × 9 pixels to better show the structure in the UV continuum and facilitate the comparison with the structures in the low-resolution ground-based Hα images.

COLINA et al. (see 488, L72)

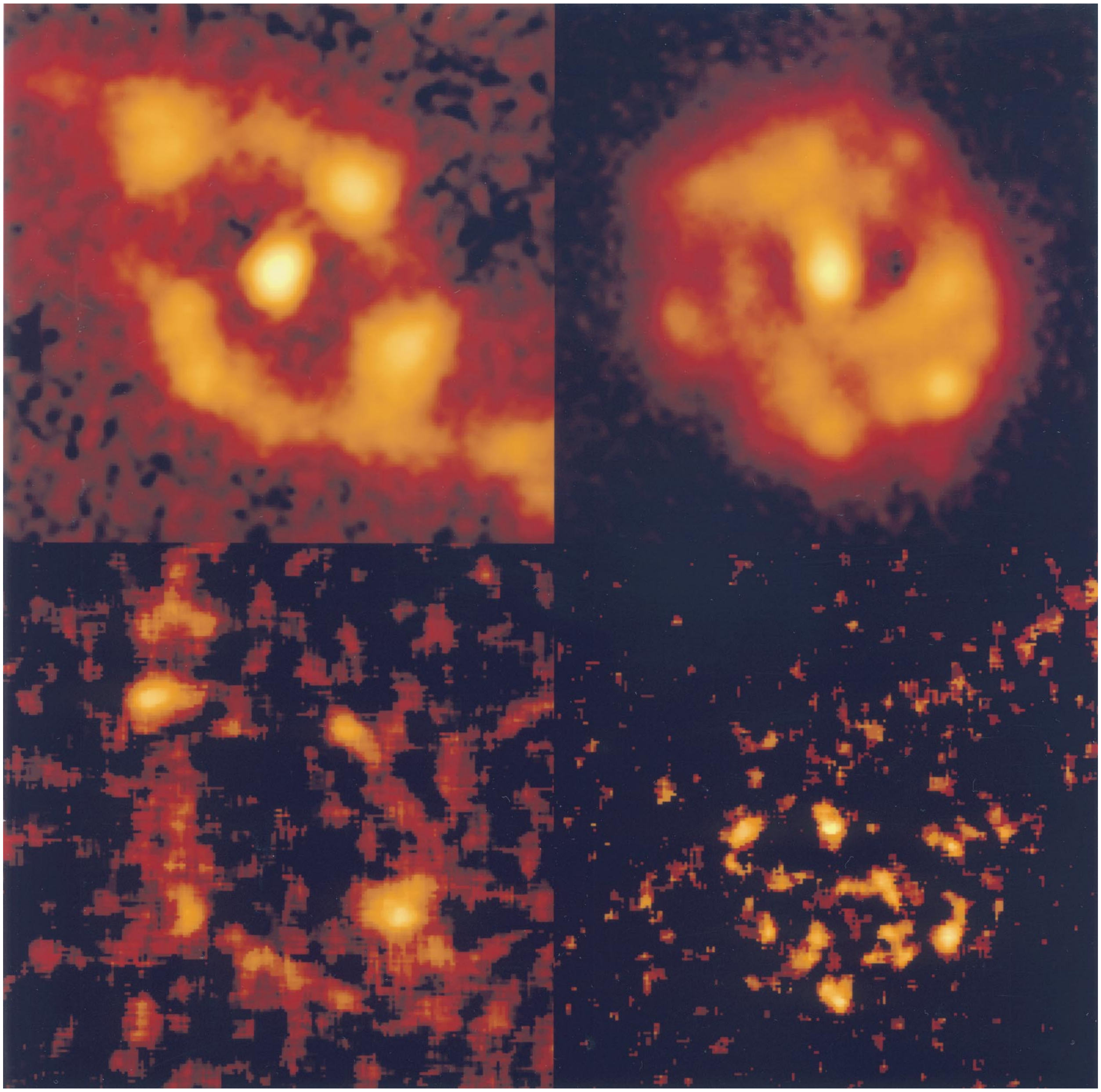

Fig. 2.—Composite image showing the Hα images of NGC 5427 (*top left*) and NGC 5953 (*top right*) and the filtered WFPC2 ultraviolet images (NGC 5427: *bottom left*; NGC 5953: *bottom right*). The images are oriented with north up and east to the left. Each Hα and UV image is 20″ on a side. Details regarding the Hα images can be found in González Delgado et al. (1997). The original WFPC2 ultraviolet images have been filtered with a median filter of 9×9 pixels to better show the structure in the UV continuum and facilitate the comparison with the structures in the low-resolution ground-based Hα images. A spurious elongated structure appears in the upper right-hand corner of the filtered WFPC2 image of NGC 5953. This is due to the amplification by the filtering process of a residual noise in the original WFPC2 image of NGC 5953.

Colina et al. (see 488, L72)