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Nuclear activity in two spiral galaxies with jets: NGC 1097 and 1598

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Summary. The barred spiral galaxies NGC 1097 and 1598 are unusual in being known to have optical jet-like features aligned with their nuclei; they also have conspicuous nuclear emission-line spectra which we have studied in some detail in an attempt to throw light on the underlying activity. The very nuclei are either classic 'Liners' (NGC 1097) or quite similar to 'Liners' (NGC 1598), and are surrounded by giant H II complexes with typical low-excitation H II region spectra. The presence of near-solar abundances of N and O in these H II regions, and thus presumably also in the nuclei themselves, supports power-law photoionization models for the excitation of 'Liners' in general, in preference to available shock models. Since 'Liner' spectra are now known to be common in galactic nuclei, it is not clear that these results bear any relation to the jets; but it could be of interest to search for more jets in galaxies containing 'Liners' at a deep and uniform level of sensitivity.

1 Introduction

NGC 1097 is a southern hemisphere barred spiral galaxy which displays several remarkable peculiarities. The nuclear region was shown by Burbidge & Burbidge (1960) and Sérsic & Pastoriza (1965) to consist of a central condensation surrounded by a nearly complete 1.5 kpc diameter ring of H II regions and hotspots. The ring has been studied spectroscopically by several groups (e.g., see Osmer, Smith & Weedman 1974; Meaburn *et al.* 1981; Talent 1982), and excellent photographs have been published (Osmer *et al.* 1974; Rickard 1975). This same

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structure has also been detected at 10μm (Telesco & Gatley 1981) and, most recently, in the radio at 6 and 20 cm (see Wolstencroft, Perley & Tully 1984, and references therein). All of these observations are apparently consistent with an ongoing burst of star formation in the ring which has led to a high supernova rate.

The properties of the amorphous nucleus inside the ring are less well determined. Radio mapping with the VLA has revealed the presence of a weak, compact, flat-spectrum source at this location (Wolstencroft *et al.* 1984). In the optical, a strong continuum dominated by late-type stars is observed at the same position (Talent 1982). A decade ago, Smith (1972) noted that the [N II]/Hα intensity ratio changed from $\leqslant 1$ in the H II regions in the ring to a value >1 in the nucleus. This observation was confirmed by Meaburn *et al.* (1981) who further commented on the very broad ($\sim 500\,\mathrm{km\,s^{-1}}$) profiles of the nuclear emission lies. Meaburn *et al.* suggested that the nucleus might actually be that of a type 2 Seyfert galaxy. However, Keel (1983a) has since identified the emission as being that of a 'Liner' (see Heckman 1980).

Outside the nuclear region, NGC 1097 shows distortions in its spiral structure which imply some sort of tidal interaction with its close elliptical companion NGC 1097A (see Arp 1966; Wolstencroft & Zealey 1975). However, even more remarkable are the four optical jets, directed radially from the nucleus and extending out to projected distances as large as 90 kpc, which were discovered by Wolstencroft & Zealey (1975), Arp (1976), and Lorre (1978). These jets occur in two pairs and have been conjectured by Wolstencroft *et al.* (1984) to be thermal bremsstrahlung emission (on the basis of non-detection of 20-cm radio, X-ray, and optical spectral line emission) from ambient material swept up by high speed particles ejected from the nucleus. The colours of the jets are consistent, however, with their being composed of late-type stars (Carter, Allen & Malin 1984).

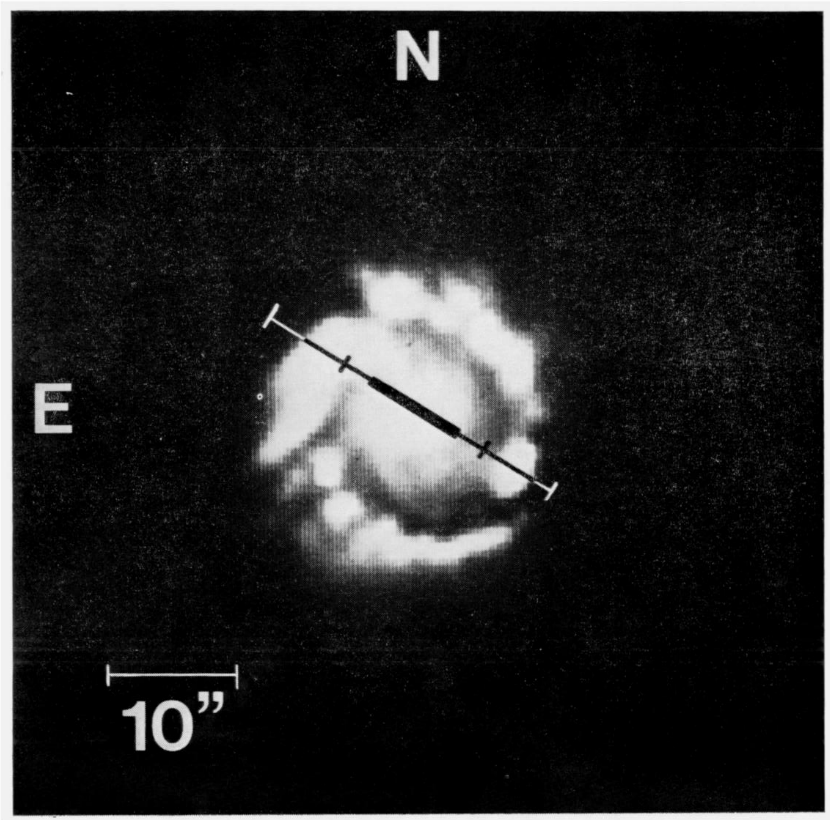
Another barred spiral galaxy which shows similar jet-like structures emanating from its nucleus is NGC 1598. This object is a member of a trio of galaxies which includes the 'Carafe' that was studied by Hawarden *et al.* (1979). The nuclear spectrum published by these authors exhibits strong narrow emission lines. Like NGC 1097 and many other spiral galaxies (Burbidge & Burbidge 1965), the [N II] 6584 and Hα lines are comparable in intensity. Little else is known about the optical or radio characteristics of this galaxy, which (judging from its redshift of $5100\,\mathrm{km\,s^{-1}}$) is four times as far away as NGC 1097.

In light of the unusual presence of optical jets in these two spiral galaxies further optical observations of their nuclei are of particular interest. We recently obtained a series of optical spectra of both NGC 1097 and 1598 as part of a larger progamme to investigate N and O abundances in the nuclei of spiral galaxies. In this paper, we present results from these observations and attempt to provide a more complete description of the nuclear activity.

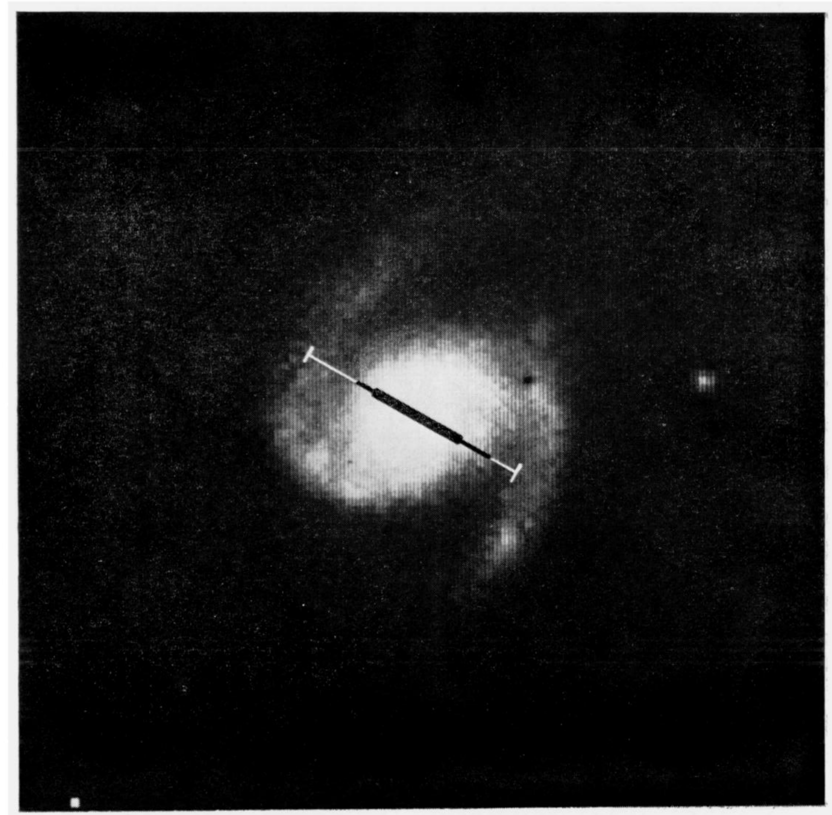
2 Observations

Long-slit spectra through the nuclei of NGC 1097 and 1598 were taken in 1981 October with the Image Photon Counting System (IPCS) (Boksenberg & Burgess 1973) at the Cassegrain focus of the 3.9-m Anglo-Australian Telescope (AAT). The spectrograph slit width was ~1.3 arcsec which, at the two dispersions employed, yielded spectral resolutions of 6 and 1.5 Å. The low-dispersion data covered the wavelength range 3500–7500 Å, while two grating tilts were observed at the higher dispersion corresponding to 4220–5150 Å and 6100–7025 Å, respectively. All spectra were reduced and calibrated in the normal fashion with the final flux scale derived from observations of several white dwarf standards from the list of Oke (1974).

The positioning of the spectrograph slit for both galaxies is illustrated in Plate 1, which shows Hα interference filter images taken with the prime focus CCD camera of the Cerro Tololo Inter-American Observatory 4-m telescope. The position angles of 57° (NGC 1097) and 60° (NGC 1598) are in both cases roughly perpendicular to the main galaxy bars.



NGC 1097



NGC 1598

Plate 1. Hα interference filter (118 Å FWHM bandwidth) CCD images of the nuclear regions of NGC 1097 and NGC 1598. The slit positions of the IPCS spectroscopic observations are indicated. The black bars show the regions included in the nuclear spectra. The NE and SW portions of the ring of H II regions in NGC 1097 where spectra were extracted are indicated by the outer sets of tick marks; for NGC 1598 the H II region spectra were summed on both sides of the nucleus between the black bar and the outer tick marks.

3 Results

3.1 NGC1097

Our low-dispersion IPCS spectrum of the nucleus of NGC1097 is shown in Fig. 1. For comparison, two additional spectra are included. The lowest one is from the same observation, extracted from where the slit passed over the NE portion of the ring of H II regions. The middle one is the nuclear spectrum of a normal elliptical galaxy, NGC7145, taken the same night with the same instrumental configuration. The very distinct characters of the ring and nuclear regions in NGC1097 are at once apparent. The ring spectrum shows strong emission lines of uniformly low ionization. In contrast, the nuclear spectrum has much weaker emission lines, but showing clear evidence of a wide range in ionization. The previously-mentioned reversal of the [N II] 6584/Hα ratio from the ring to the nucleus is accompanied by an equally notable reversal of the [O III] λ5007/Hβ ratio from $\ll 1$ in the ring of H II regions to >1 in the nucleus. The higher dispersion spectra (reproduced in Figs 2 and 3) also show the striking broadness of the nuclear emission line profiles previously reported by Meaburn *et al.* (1981).

The continuous spectra observed in the nucleus and the surrounding ring are likewise distinct. That associated with the ring is very blue, with the Balmer series clearly in absorption (see especially Fig. 2). These properties point to the presence of a substantial population of young hot stars. However, as Talent (1982) pointed out, the nuclear continuum is dominated by late-type stars and, as Figs 1–3 show, is virtually indistinguishable from that of an elliptical galaxy.

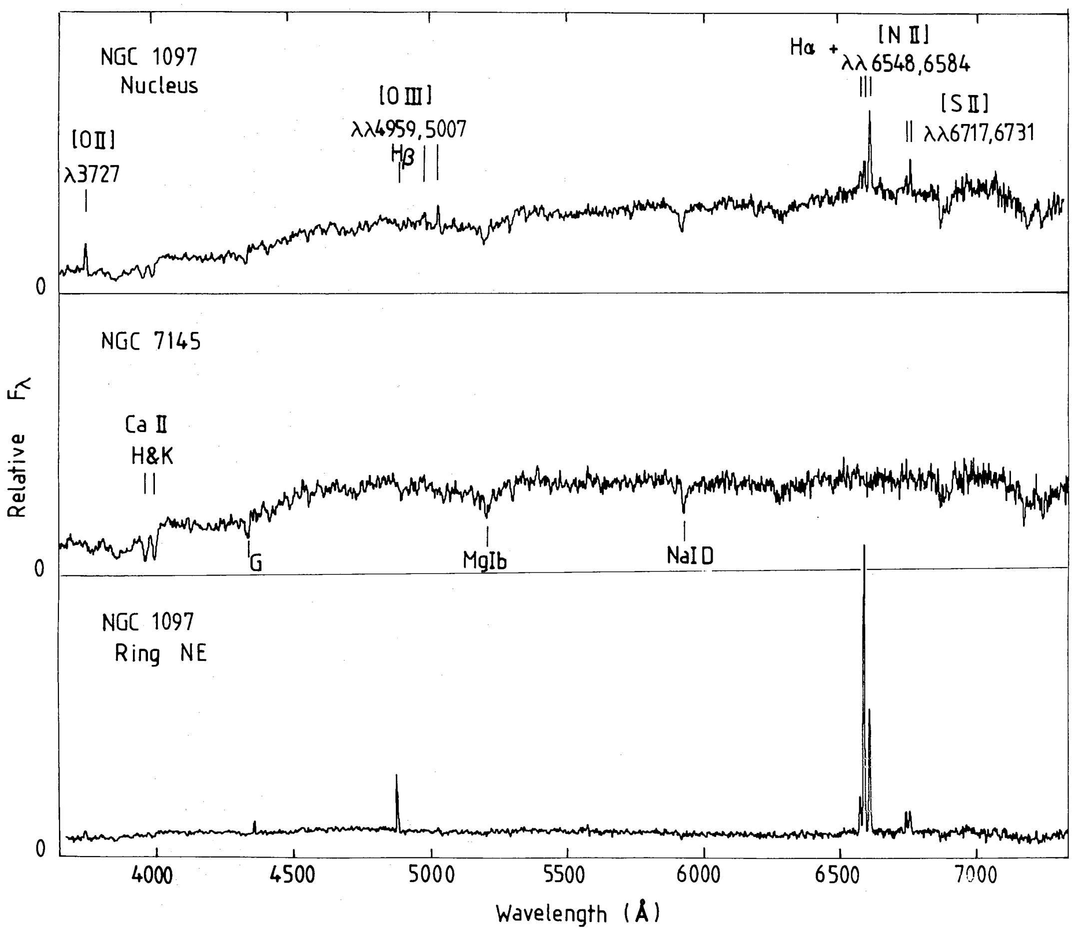


Figure 1. Low-dispersion (6 Å FWHM) IPCS spectra of the nucleus of NGC1097 (top), the NE portion of the ring of H II regions surrounding the nucleus (bottom), and the nucleus of the elliptical galaxy NGC 7145 (middle).

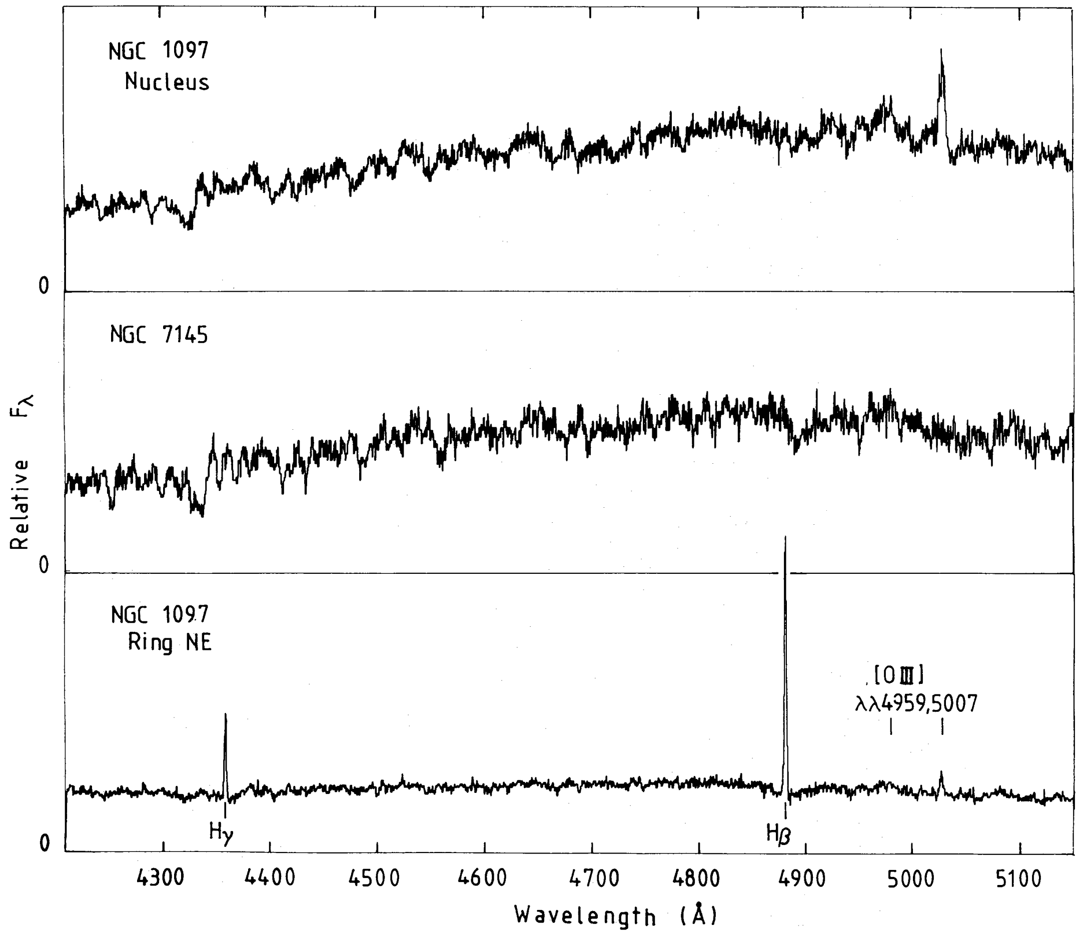


Figure 2. High-dispersion (1.5-Å FWHM) IPCS spectra of the same regions in NGC1097 and 7145 shown in Fig. 1, covering the wavelength range from Hγ to [O III] λ5007.

Table 1. Reddening-correlated relative emission-line intensities for NGC1097. Abundances derived for the ring H II regions are also given.

Line		$I(\lambda)/I(\mathrm{H}\beta)$ Ring NE	SW	Nucleus
[O II]	3727	0.50b	1.05b	6.12a
[Ne III]	3868	—	—	1.34b
Hγ	4340	045b	0.45b	0.44c
Hβ	4861	1.00a	1.00a	1.00b
[O III]	4959	—	—	1.06b
[O III]	5007	0.10a	0.13b	2.91a
[O I]	6300	—	<0.067 (2σ)	1.00c
[N II]	6548	0.37a	0.41a	1.50a
Hα	6563	2.95a	2.95a	2.95a
[N II]	6584	1.26a	1.32a	4.94a
[S II]	6716	0.19b	0.32b	1.07c
[S II]	6731	0.19b	0.30b	1.70c
c		1.4	1.6	0.9
A_V (mag)		3.0	3.5	1.9
12+log(O/H)		9.40	9.28	—
$\langle t \rangle$		0.46	0.52	—
log(O/N)		0.77	0.87	—

Note: Estimated precision— a≤10 per cent; b≤20 per cent; c≤30 per cent.

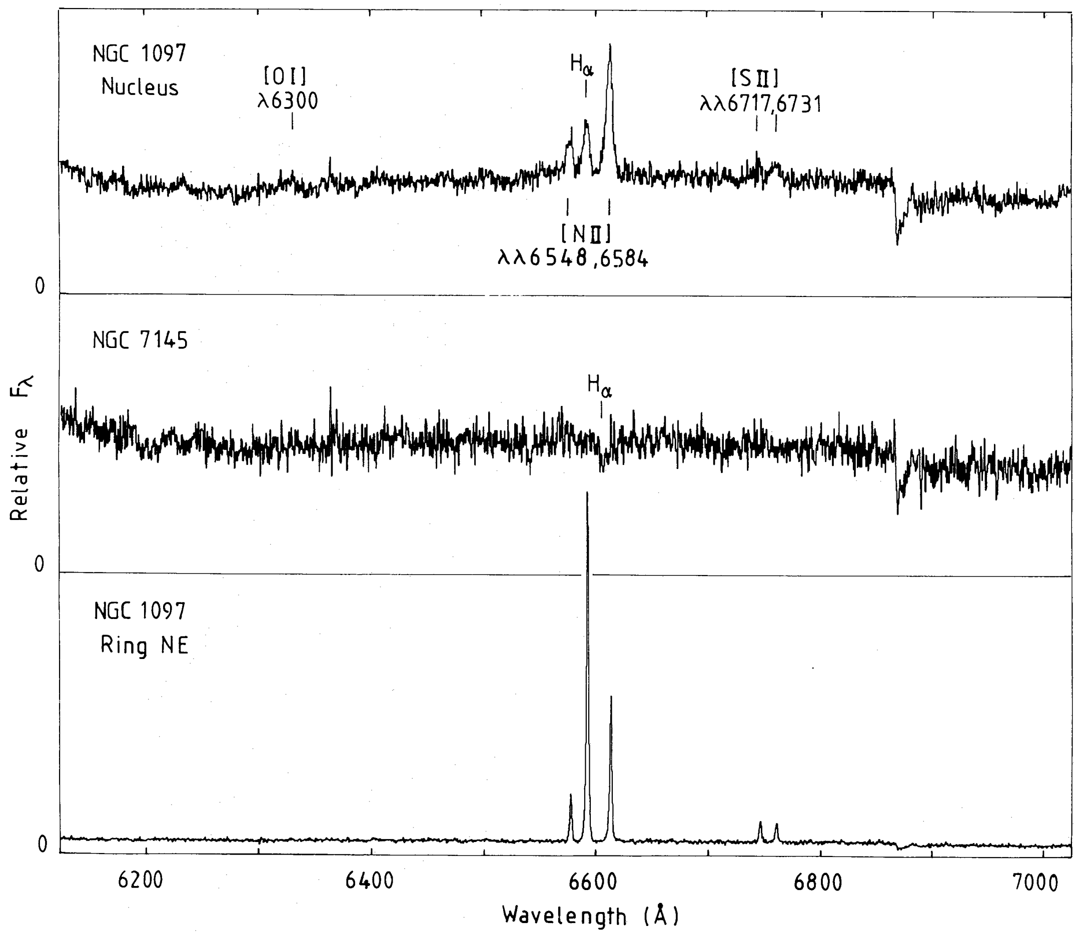


Figure 3. High-dispersion (1.5-Å FWHM) IPCS spectra of the same regions in NGC1097 and 7145 shown in Fig. 1, covering the wavelength range from [O I] λ6300 to [S II] $\lambda\lambda$6716, 6731.

Reddening-corrected emission line intensities measured from the IPCS spectra for both the nucleus and the two positions in the H II region ring that the slit crossed are listed in Table 1. In view of the weakness of the nuclear emission lines, we subtracted the underlying continuum using a scaled version of our spectra (taken the same nights) of the elliptical galaxy NGC7145. Examples of this procedure are displayed in Fig. 4. As might be expected, the Balmer emission lines are affected the most by the underlying stellar absorption. Line intensity measurements made of the nuclear spectrum without taking into account the continuum absorption would lead to a serious overestimate of both the [O III] λ5007/Hβ and [N II] λ6584/Hα ratios.

The relative line intensities in the ring are typical of those in the most metal-rich H II regions found in the discs of spiral galaxies (see Pagel & Edmunds 1981). For example, H II regions I and III observed by Dufour *et al.* (1980) in M83 have virtually identical spectra to the NE and SW ring positions, respectively, in NGC1097. Using the procedures of Pagel, Edmunds & Smith (1980), with a small revision at the high-abundance end of the calibration, we derive the O/H and N/O abundances given in Table 1. Although the oxygen abundance exceeds solar by up to a factor of ~3, the N/O ratio is only slightly larger than solar.

The ionization mechanism in the nucleus is quite different. This is shown in Fig. 5, where the nucleus is seen to lie significantly off the locus of H II region measurements in the [O III] λ5007/Hβ vs [N II] λ6584/Hα plane. As discussed by Baldwin, Phillips & Terlevich (1981), this is the same area of the diagram which the so-called 'Liner' galaxies (see Heckman 1980) occupy.

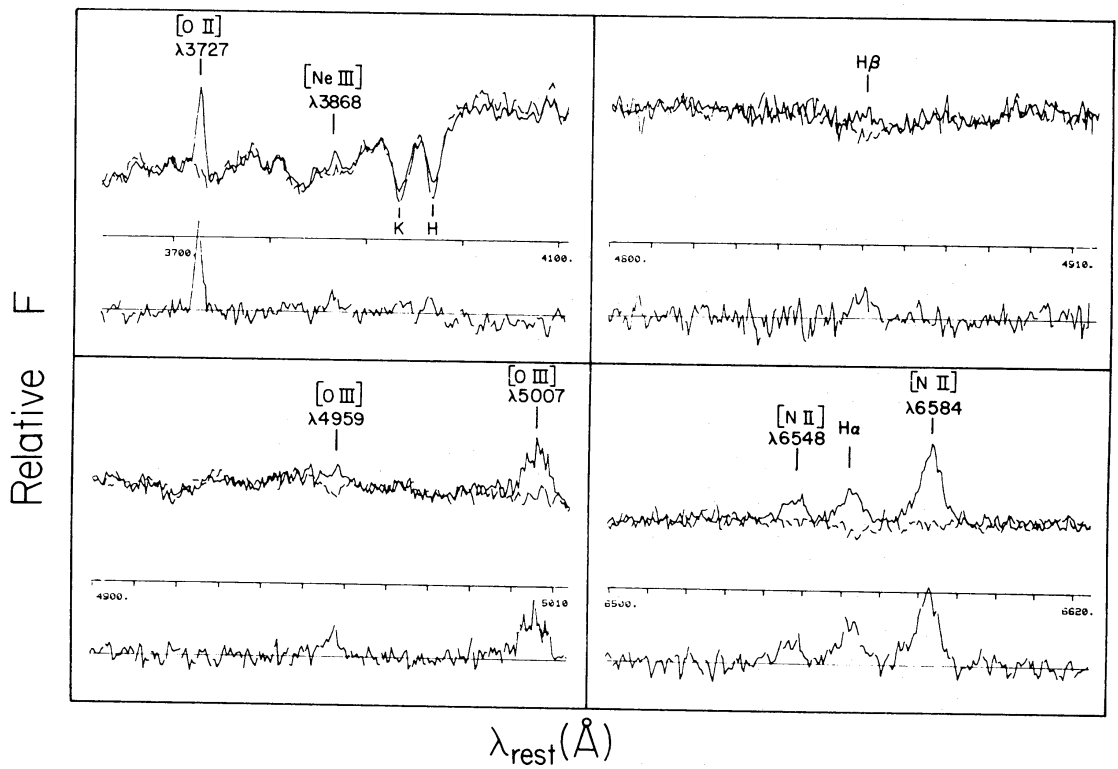


Figure 4. Examples of subtraction of the late-type stellar continuum in the nuclear spectrum of NGC1097 using a scaled version of the corresponding spectral regions in the elliptical galaxy NGC7145. In each case, the spectra of NGC1097 and 7145 are plotted as solid and broken lines, respectively.

Table 2. Reddening-corrected line intensities in the nuclear region of NGC1598.

Line		$I(\lambda)/I(H\beta)$ Outside, perpendicular to bar (5–12 arcsec or 2–5 kpc)	Nucleus (central 5 arcsec or 2 kpc)
[O II]	3727	1.51b	1.08b
Hγ	4340	0.38c	0.49b
He II	4686	<0.2 (2σ)	0.23
Hβ	4861	1.00a	1.00a
[O III]	4959	0.22c	0.44a
[O III]	5007	0.50a	1.35a
He I	5876	0.10:	0.15c
[O I]	6300	<0.1 (2σ)	0.12b
[N II]	6548	0.47a	0.91a
Hα	6563	2.82a	2.95a
[N II]	6584	1.29a	3.02a
[S II]	6716	0.37b	0.31b
[S II]	6731	0.19b	0.25b
c		1.2	0.9
A_V (mag)		2.6	1.9
12+log(O/H)		9.08	—
$\langle t \rangle$		0.59	—
log(O/N)		0.87	—

Estimated precision: a≤10 per cent; b≤20 per cent; c≤30 per cent; : uncertain.

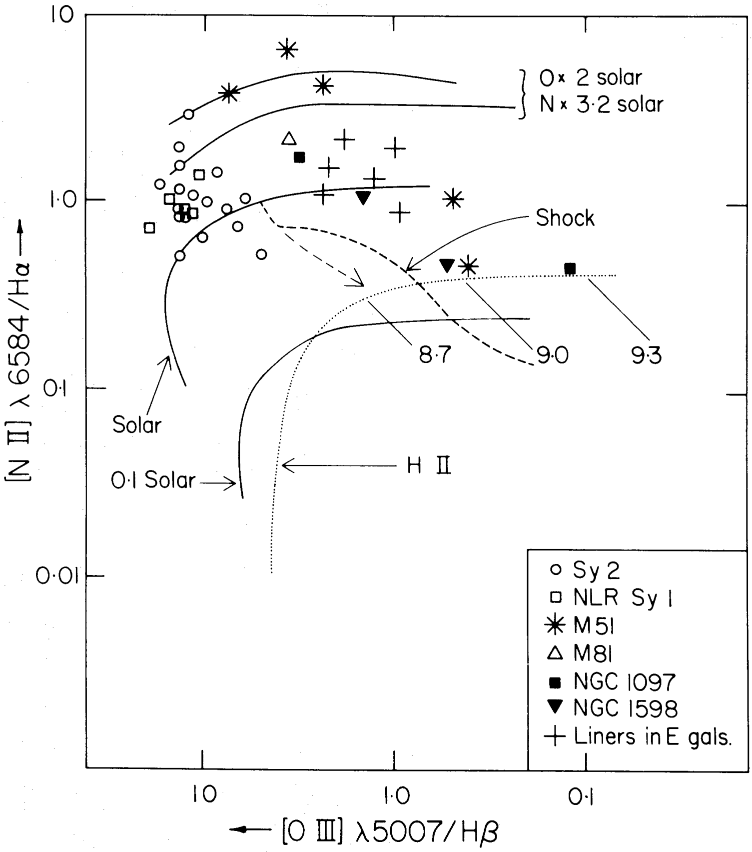


Figure 5. [N II], [O III] diagram for NGC1097 and 1598, together with Seyfert 2 galaxies and 'Liners' in elliptical galaxies (after Ferland & Netzer 1983). Also plotted are corresponding data for M51 (Rose & Searle 1981). Solid curves are predictions from power-law photoionization models for solar and 1/10 solar abundances (Ferland & Netzer 1983, and private communication: the two top curves are for slightly different cut-offs and power-law slopes); broken curves are from shock models with solar abundances (Shull & McKee 1979), the arrow representing a uniform reduction in the abundances by a factor of 3 (after Dopita *et al.* 1984). The dotted curve is the locus for H II regions (after Baldwin, Phillips & Terlevich 1981), with oxygen abundances 12+log(O/H) indicated after a slight modification of the calibration of [O III]/[N II] by Pagel, Edmunds & Smith (1980).

3.2 NGC1598

In Fig. 6, we show spectra of the nucleus of NGC1598, and of its surroundings, at low resolution. Relative line intensities and abundances are given in Table 2. As in the case of NGC1097, the intensity ratios [N II]/Hα and [O III]/Hβ increase sharply as one goes into the very nucleus, indicating the likely presence of a 'Liner', but the effect is somewhat less strong and the hot-star continuum persists right through the nucleus, probably because at the distance and inclination of NGC1598 the innermost H II regions cannot be resolved in ordinary seeing. That the [O III]$\lambda\lambda$4959, 5007 emission in the nucleus is largely due to a 'Liner' is supported by the noticeably broader profile of these lines as compared with Hβ. The nuclear spectrum (see Fig. 6) is thus a composite of H II region and 'Liner' in unknown (and perhaps wavelength-dependent) proportions.

4 Discussion and conclusions

The Liner emission line spectrum is often associated with active nuclei, although it has been found in many 'normal' spirals (Heckman 1980; Stauffer 1982; Keel 1983a, b). Heckman (1980) has shown that galaxies possessing such nuclear spectra are also frequently observed to have

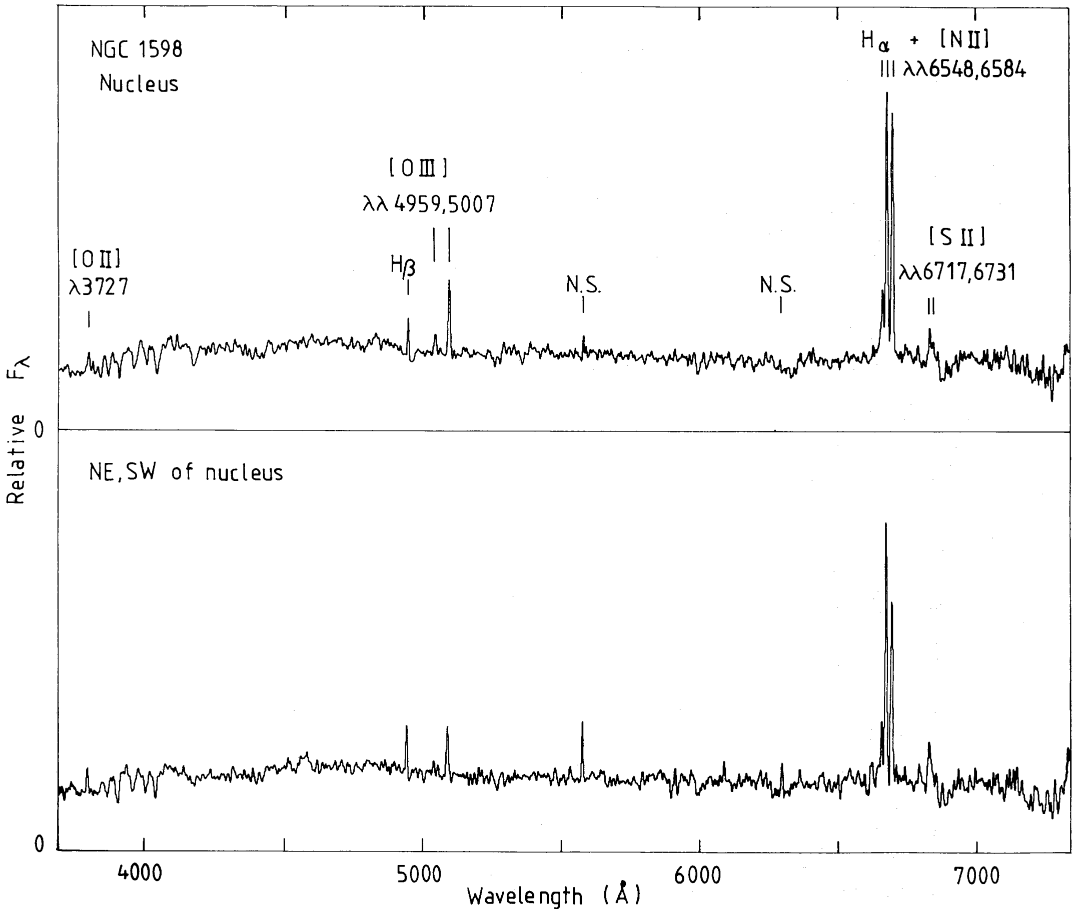


Figure 6. Low-dispersion (6-Å FWHM) IPCS spectra of the nucleus of NGC 1598 (top) and surrounding H II regions to both the NE and SW of the nucleus (bottom).

compact, flat-spectrum nuclear radio sources. As previously mentioned, the nuclear radio source in NGC 1097 falls into this category, although like the optical emission lines, this source is relatively weak. Heckman concluded that the ionization of the gas in Liners is produced predominantly by $\sim 100\,\mathrm{km\,s^{-1}}$ shocks. More recently, several investigators (Keel 1983a; Ferland & Netzer 1983; Halpern & Steiner 1983) have suggested that the same emission line spectrum can arise from gas which is photoionized by a power-law source of radiation. The emission lines in the nuclei of NGC 1097 and 1598 are too weak for us to decide which of these models is more appropriate (e.g., we cannot place interesting limits on the strengths of the important He II λ4686 and [O III] λ4363 lines as was done for some objects of rather different nature by Osterbrock & Dahari 1983). However, we can obtain some indications if we assume the nuclear abundances to be the same as in the surrounding H II regions, and compare with model sequences based on photoionization and on shock models respectively (*cf.* Pagel 1983).

Fig. 5 shows the positions of the objects we have observed, and a few other objects, in the [O III], [N II] diagram which represents the line ratios that are easiest to measure. We have plotted two points for our objects in this diagram, the upper one representing the nucleus and the lower one the average of the two regions on either side. We show also the loci of photoionization models computed by Ferland & Netzer (1983, and private communication) for solar, 3×solar and 1/10 solar abundances (with ionization parameter increasing to the left), the shock models for solar abundances computed by Shull & McKee (1979) (with shock velocity increasing to the left), the models of Dopita *et al.* (1984) for high-speed shocks with abundances ranging from solar to 1/3 solar, and the locus for H II regions after Baldwin *et al.* (1981), with oxygen abundances

12+log(O/H) indicated after the revised calibration of [O III]/[N II] by Pagel *et al.* (1980). As in the case of M51 (Rose & Searle 1982), the data for any one galaxy lie close to a mixing line extending from pure H II region with a given O-abundance to more or less extreme spectra in the region occupied by 'Liners'. The region occupied by Seyferts and 'Liners' is well covered by the photoionization models for solar and somewhat larger abundances, corresponding to those that we find in the surrounding H II regions, with the more-or-less horizontal sequence of Seyferts and 'Liners' corresponding to constant abundances and changing ionization parameter. Shock models can also be fitted, with appropriate abundances, but if pure 'Liners' actually form a horizontal sequence as the data collected by, e.g. Baldwin *et al.* (1981) suggest, then either the shock-velocity sequence of Shull & McKee (1979) or the abundance sequence of Dopita *et al.* (1984) requires steep increases in the N/O ratio as one goes to the right in the diagram. Since there is no other reason to believe in such steep increases in N/O, either with diminishing shock velocity or with diminishing O-abundance, these results would seem to offer more support to the photoionization models. Some of the finite-age high-velocity shock models of Binette, Dopita & Tuohy (1984) may overcome this particular objection, but the typical finite-age sequence illustrated by them involves a steep increase in [O I] intensity with the age of the shock which is not supported by the observational data for 'Liners' in general. The case of NGC 1598 shows that this support for the photoionization models could be weakened if it were to turn out that the pure 'Liners' are all close to NGC 1097 in plots such as Fig. 5 and those to the right in the diagram are adulterated by H II region emission; but this not very likely to be the case for the 'Liners' in elliptical galaxies which we show there. Clearly more high-resolution (both spatial and wavelength) spectra of the type we have obtained will be necessary before a more definitive answer can be made.

In the Baldwin *et al.* (1981) plots of [O I] and [O III] against [O II]/[O III], the 'Liner' nucleus of NGC 1097 lies on Ferland & Netzer's locus for 1/3 solar oxygen abundance and NGC 1598 lies lower still, but is undoubtedly affected by H II region emission. We do not give much weight to these apparent indications of low oxygen abundance because the separation of the curves for solar and 1/3 solar is small and the [S II] ratio in NGC 1097 indicates a fairly high electron density ($\sim 5\times10^3\,\mathrm{cm}^{-3}$) in which case [O II] will be affected by collisional de-excitation.

The detection of 'Liners' in NGC 1097 and 1598 is of interest because, as mentioned earlier, these galaxies also show faint optical jets. Many elliptical galaxies with radio and/or optical jets contain 'Liners' in their nuclei. Examples are M87 (Stauffer & Spinrad 1979; Ford & Butcher 1979), NGC 5128 (Möllenhoff 1981; Phillips 1981), 3C236 (Miley & Osterbrock 1979), and NGC 6251 (Miley & Osterbrock 1979). Like NGC 1097, these galaxies also have compact flat-spectrum nuclear radio sources. However, the luminosities of both the 'Liner' and compact radio sources in NGC 1097 are small, even when compared to the 'Liners' and radio sources found in other spiral galaxy nuclei (Heckman 1980; Keel 1984). This fact, along with the recent realization that the 'Liner' class includes a majority of spiral galaxies, raises the considerable doubt as to whether the optical jet-like features in both NGC 1097 and 1598 are a consequence of nuclear activity. But, a search for optical or radio jets in other spiral galaxies with 'Liner' nuclei would seem to us a worthy project, especially since nearly all of the 'Liners' discovered to date are northern hemisphere objects, covered only by the Palomar Sky Survey plates which are not deep enough to detect jets of the same surface brightness as those observed in NGC 1097. It is also possible that the jets and nuclear activity have a common cause, perhaps in the interaction (or merger) of the galaxy with a companion. An interacting companion is already known for NGC 1097, and NGC 1598 is a member of a small group. The interaction might cause a dynamical ejection of stars (if the jets are stellar – although the apparent collimation would be an obvious problem) and also spill gaseous or stellar fuel on to the nuclear energy source, powering the nuclear activity and jets (if non-stellar).

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