Spectropolarimetry of the Circinus galaxy

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Abstract. High quality 4500–6800 Å spectropolarimetric observations of the Circinus galaxy are reported. These show polarized and relatively broad (FWHM≈3300 km/s) Hα (as well as marginal Hβ) arising from a <3″ (<60 pc) region centered on the nucleus and coincident with the peak of the narrow line region. Broad Hα might also be present ∼8″ (160 pc) SE from the nucleus and close to the dust lane, but the result is only marginal and should be verified by higher s/n data. The continuum is dominated by stellar emission with ≤3% contribution from the scattered AGN continuum, and all the light (i.e. all the stellar continuum and narrow lines) is polarized, most probably by transmission through and scattering by dust in the disk. The data are compatible with a simple model where the scattered broad lines and AGN emission are quite polarized (P≈25%) but account for only 1% of the observed continuum. The scattered broad Hα has an equivalent width Wλ≈400 Å, a flux similar to the narrow Hα and a luminosity ≃5 105 L⊙. Assuming an efficiency of 1% for the BLR mirror, the intrinsic luminosity of the broad Hα is roughly 5 107 L⊙ and ≃0.5% of the FIR luminosity, a ratio similar to those found in type 1 Seyferts. Specific prediction for future observations are also presented.

Key words: Galaxies: Seyfert – Galaxies: individual: Circinus

1. Introduction

After the discovery of polarized broad lines in NGC1068, spectropolarimetry has become a standard tool to trace hidden broad line regions (BLR) in objects like type 2 Seyferts where BLR and AGN continuum are visually obscured (cf. Antonucci 1993 for a review). In the standard model ≈1% of the BLR photons are scattered toward us by a ‘mirror’ (dust or free electrons) lying outside the obscuring ‘torus’, and the light appears partly polarized. Seyferts 2 with polarized BLR are usually characterized by prominent narrow lines onto a mixture of stellar and non stellar (featureless) continua, and the latter accounts for a significant fraction (>10%) of the total observed continuum flux. The narrow lines are much less polarized than the continuum and [OIII] is often (but not always) unpolarized. The stellar flux is also basically unpolarized and is subtracted using suitable stellar templates to obtain the ‘true’ polarization of the non stellar nuclear emission (e.g. Miller & Goodrich 1990).

The Circinus galaxy is an anonymous, nearby (∼4 Mpc) spiral lying very close to the galactic disk (b=−3.8°) in a region of relatively low Galactic extinction (A_V≈1.5 magnitudes, Freeman et al. 1977). Its Seyfert 2 activity was already suspected on the basis of IR colours (Moorwood et al. 1994, hereafter O94, Moorwood et al. 1996), optical line images showing a spectacular [OIII] cone and Hα starburst ring (Marconi et al. 1994, hereafter M94), and X–rays spectroscopy revealing a very prominent Fe–K line (Matt et al. 1996). Being very bright and ∼5 times closer than NGC1068, the Circinus galaxy is the ideal laboratory to study the Seyfert 2 phenomenon. The only drawback is that the object cannot be easily studied in the UV because the central ∼3″ regions suffer by significant local extinc- tion (A_V≳3 mag), and this absorption strongly varies with position. To our knowledge, no spectropolarimetric observations of this galaxy exist.

This letter presents for the first time spectropolarimetric observations of this galaxy. The observations and results are described in Sect. 2, 3 while Sect. 4 presents a simple model which is also used to estimate the intrinsic properties of the obscured BLR.
2. The data

The spectra were collected on March 7 1997 using EFOSC1 mounted on the ESO 3.6m telescope. The detector was a Tek 512x512 CCD array with 27\AA (0.61\arcsec sky projected angle) pixels and the instrument setup included a rotating \(\lambda/2\) plate and a Wollaston prism in the collimated beam, and the disperser was the low resolution (\(\sim6.5\) \AA/pixel) ESO B300 grism. The 2\arcsec broad slit was aligned at PA=318\degree, roughly along the [OIII] cone axis and perpendicular to the galaxy disk (Fig. 1). Twenty exposures with a total integration time of 5 hours were collected, and consisted of five cycles of four 15 minutes exposures with the \(\lambda/2\) plate rotated by 0, 22.5, 45 and 67.5 degrees. Measurements of polarized (HD126593, HD298383), unpolarized (HD64200) and spectroscopic (Hiltner 600) standard stars were also performed for calibration purposes. Standard reduction of the 2D frames was applied and three spectra were extracted at different positions along the slit (cf. Fig. 1 and the caption of Fig. 2), the total flux spectra are shown in Fig. 2.

The polarimetric reduction of the 1D spectra was performed using the software written by J.R. Walsh under the MIDAS environment and the resulting linear polarization degree \(P_{\text{obs}}\) and position angle \(\theta_{\text{obs}}\) are displayed in Fig. 2. These quantities must be corrected for the polarization by our Galaxy whose polarization vector can be first estimated from the spectra of the foreground star (Fig. 1) which yield \(P_{\text{V}}=1.8\%\) at \(\theta=68\degree\), an angle equal to that found in the NW spectrum. The corrected spectra are \(P_{\text{corr}}\) and \(\theta_{\text{corr}}\) which are also plotted in Fig. 2 where the polarization degree of NW decreased to \(\sim0.8\%\) while its angle remained \(\sim68\degree\) and equal to the galactic polarization angle. This indicates that the NW spectrum may be intrinsically unpolarized and the correct amount of Galactic polarization could therefore be \(\sim2.6\%\) and larger than that suffered by the foreground star which is probably too close to properly sample the whole disk of our Galaxy. Using \(P_{\text{V}}=2.6\%\) the corrected spectra become \(P'_{\text{corr}}\) and \(\theta'_{\text{corr}}\) which are plotted in the bottom rows of Fig. 2. The true polarization degree of the Circinus spectra is somewhere between \(P_{\text{corr}}\) and \(P'_{\text{corr}}\). Noticeably, the \(P\) spectra of the nucleus and of the SE region are rather independent on the details of the correction for local polarization, i.e. \(P_{\text{corr}}\) and \(P'_{\text{corr}}\) are virtually equal in the nuclear and SE spectra. However, the polarization angle does depend on the correction applied but is basically independent on wavelength in both \(\theta_{\text{corr}}\) and \(\theta'_{\text{corr}}\) (cf. Fig. 2).

3. Results

3.1. The polarized broad H\(\alpha\)

The most striking result is the prominent emission feature at 6575 \AA (observed \(\lambda\)) in the \(P\) nuclear spectrum. The center of this feature is within 100 km/s (1/10 of the instrumental resolution) of the wavelength of the narrow H\(\beta\) (cf. O94), has a full width half maximum of 72 \AA (3300 km/s) and is much broader than the unresolved H\(\alpha\)+[NII] complex in the F\(\lambda\) spectrum which has FWHM=42 \AA. The \(P\) nuclear spectrum does not show other emission/absorption features with the possible exception of H\(\beta\) which is marginally \((2\sigma)\) detected at \(\sim4870\) \AA. In particular, no significant variation of \(P\) and \(\theta\) is visible at the position of the prominent [OIII] and [SII] narrow lines, and this indicates that [NII] does not contribute to the broad H\(\alpha\), but rather dilutes it (see also Sect. 4.2).

The spatial extent of the broad H\(\alpha\) was estimated from a row-by-row polarimetric reduction of the 2D spectra. The resulting distribution along the slit is peaked on the nucleus, concentrated within \(<3''\) and basically unresolved. Interestingly however, some broad H\(\alpha\) emission seems to reappear \(\sim8''\) SE of the nucleus, and this causes
Fig. 2. Extracted spectra along the slit (cf. Fig. 1), ‘nucleus’ is 2″x5″ centered on the optical peak which is coincident within 0.3″ with the IR nucleus (M94), ‘SE’ is 2″x6″ centered 7″ SE of the nucleus and toward the dust lane (cf. Figs. 1, 2 of M94) and ‘NW’ is 2″x5″ centered 5″ NW of the nucleus and within the [OIII] cone (cf. Fig. 1). Wavelengths are in Å and \( F_\lambda \) is in units of \( 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\). The observed linear polarization degree and angle are \( P_{\text{obs}} \) and \( \theta_{\text{obs}} \) while \( P_{\text{corr}} \), \( \theta_{\text{corr}} \) and \( P'_{\text{corr}} \), \( \theta'_{\text{corr}} \) are the values corrected for local polarization using two different estimates of the galactic polarization vector (cf. Sect. 2). Note that the spectra have the original resolution.

the marginal detection of broad H\(\alpha\) in the SE \( P \) spectrum (cf. Fig. 2). This indicates that another BLR mirror may exist \( \gtrsim 150 \) pc SE from the nucleus and in the direction of the dust lane, but the evidence is only marginal. Higher s/n spectra are required to verify this possibility.

3.2. Dilution of the scattered nuclear spectrum

The standard method to determine the intrinsic polarization properties of the nuclear spectrum is to estimate the contribution of stellar flux to the observed continuum, and correct for it assuming that the diluting stellar continuum is unpolarized. The stellar template normally used for this purpose is that of an old stellar system (e.g. M32), but this provides a very poor fit to the Circinus galaxy whose spectrum shows strong H\(\beta\) absorption and other features typical of B-A stars associated to a relatively young (circum)nuclear starburst whose presence is also demonstrated by other observational evidences (e.g. Oliva et al. 1995).

A much more accurate, and indeed the most natural stellar template is the NW spectrum which is intrinsically unpolarized and does not show any trace of the scattered nuclear component. A comparison between the nuclear and NW spectra is shown in Fig. 3 where the most remarkable result is that the equivalent width of the stellar features is the same in both spectra, and the maximum contribution from a featureless continuum is only \(<3\%\) of the total observed flux. A straight correction for the stellar dilution is therefore impossible.

4. Discussion

4.1. Origin of the continuum polarization

The observed \(~2\%\) continuum polarization is very difficult to interpret in terms of scattered nuclear light diluted by unpolarized stellar emission because this would require an unreasonably large (\(>70\%\)) intrinsic polarization. Besides, in such a scenario the \( P \) spectra should contain narrow [OIII], [SII] absorption, unless the NLR intrinsic polarization is finely tuned to avoid this effect.

The most natural interpretation is that all the light (i.e. stars, NLR and scattered BLR) is weakly polarized by either transmission through, or single scattering by the dust in the galactic disk. A highly simplified though plausible scenario is that sketched in Fig. 4 where the observer sees the extincted radiation from the stars, the NLR and the BLR mirror, plus a small fraction of ‘off-axis’ light scattered toward the line of sight by the dust in the disk of the Circinus galaxy. A non-zero polarization is ensured by the asymmetry of the dust distribution whose column density increases toward SE producing the observed sharp extinction gradient, and by the non uniform distribution
of the stellar and NLR emission which is strongly peaked on the nucleus (cf. M94). The shape of the observed $P$ spectrum depends on the relative contribution of scattering and transmission polarizations, and the latter is more important in the highly extincted SE region thus producing a flatter $P$ spectrum.

The fact that the corrected polarization angle is basically constant with $\lambda$ and does not show significant variations within the broad H$\alpha$ profile requires that the polarization by the BLR mirror and scattering/transmitting dust have similar position angles. This is not unreasonable because the corrected $\theta$ is $\sim 20^\circ$, roughly parallel to the disk and dust lane and perpendicular to the axis of the [OIII] cone (cf. Figs. 1, 2 of M94). If the BLR mirror is along the cone axis and the magnetic field is aligned with the galaxy disk, it naturally follows that all polarization angles should be similar.

4.2. The physical properties of the BLR and its mirror

A detailed treatment of the radiation transfer and scattering through the disk is beyond the aims of this paper. Here we concentrate on the properties of the BLR scattered spectrum and make the reasonable assumption that the polarization introduced by transmission/scattering through the disk could be parameterized by $P_{\text{disk}} \approx (\lambda/5500)^{-\alpha}$ where the slope $\alpha$ is $\gtrsim 2$ when single scattering by small grains dominates, while $\lesssim 0$ when the main polarization mechanism is transmission through aligned non-spherical grains. If the polarization angles are similar, and as long as the polarization degrees are small (which is our case), the observed degree of linear polarization is simply the sum of $P_{\text{disk}}$ and $P_0$, the polarization observed by ideally removing the galaxy disk. We model $P_0(\lambda)$ assuming that the nuclear scattered spectrum is polarized, while both the stellar continuum and narrow lines are unpolarized.

The results of a toy model with a 1% scattered AGN are shown in right hand panel of Fig. 4. Due to the large dilution, the value of $P_0$ is very small at all wavelengths but at the positions of the broad H$\alpha$ whose amplitude is a factor $\sim 5$ the nuclear continuum level and therefore stands out in $P_0$ because it is $\sim 5$ times less diluted than the surrounding continuum, and the same applies to the weaker H$\beta$. The narrow lines appear in absorption because they further dilute the scattered spectra, but their amplitude is very small simply because the continuum $P_0$ is very low. The effect of the disk polarization is simply to add a smooth continuum to $P_0$, and does not affect the amplitude of the emission (BLR) and absorption (NLR) lines.

Details of the model of Fig. 4 are as follows.
- Nuclear continuum: $I_\lambda \propto \lambda^{-\beta}$ scattered by a gray mirror
- $W_\lambda (\text{H$\alpha$-broad}) = 400 \; \AA$ ; $I(\text{H$\alpha$-broad})/I(\text{H$\beta$-broad}) = 3.5$
- BLR mirror extincted by $A_{V} = 5$ mag (same as NLR, cf. O94)
- Scattered spectrum has $P = 25\%$ at all wavelengths
- Nuclear scattered continuum is 1% of observed $F_\lambda$
- Stellar and NLR spectra are from high resolution EMMI data
- Polarization by the disk: $P_{\text{disk}}(\lambda) = 0.0148 (\lambda/5500)^{-2}$

These values are by no means unique because similarly good fits could be obtained by e.g. decreasing the intrinsic equivalent width of H$\alpha$ and increasing the contribution by the BLR to the total observed continuum, but the fit rapidly deteriorates for equivalent widths below 200 $\AA$ and $W_\lambda (\text{H$\alpha$}) > 150 \; \AA$ could be considered a tight lower limit.

A quite firm result is that the scattered light cannot be much bluer than assumed otherwise the broad H$\beta$ would appear too strong. This sets a tight lower limit $A_{V} > 2$ for the extinction suffered by the BLR mirror, but gives no useful information on the intrinsic spectral efficiency of the mirror whose extinction is unknown. In other words, the scattered light could equally well come from a 'gray mirror' suffering an extinction similar to the NLR (the assumption of Fig. 4) or from a 'blue mirror' suffering a larger extinction.

The best constrained parameter is the observed flux of broad H$\alpha$ which is $3 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ and translates
into $5 \times 10^5 \ L_\odot$ if the extinction toward the BLR mirror is similar to that measured for the narrow lines. Assuming a ‘standard’ mirror efficiency of 1%, the intrinsic luminosity of broad Hα becomes $5 \times 10^7 \ L_\odot$ or 0.5% of the IRAS FIR luminosity, a ratio similar to those found in many type 1 Seyferts (see e.g. Table 1 of Ward et al. 1988).

Interesting predictions of the model are the detection of circular polarization due to scattering of the linearly polarized BLR, and high resolution $P$ spectra which should reveal a stronger Hα broad component with sharp absorption features at the positions of the narrow \[\text{NII}\] and Hα lines (Fig. 4).

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