Active Nuclei and their Host Galaxies: Observations of Seyfert Galaxies

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Abstract

We repeat Carl Seyfert’s observation of M77 (NGC 1068) and calculate the B-V color index of its nucleus. We confirmed the exceptionally low color index of the M77 nucleus within the literature, but were unable to calculate that of a non-Seyfert galaxy for comparison. Given from the literature that the B-V color index is unusually low compared with non-Seyfert galaxies, we discuss qualitatively that the value must be attributable to a very high-mass, high-density non-stellar object centrally located within the nucleus.

Introduction

In the 1940’s Carl Seyfert observed that a small percentage of galaxies have very bright nuclei starlike in appearance [2]. Always spiral in structure, a galaxy of the Seyfert class is characterized by a nucleus with narrow and broad emission lines spanning a wide range of permitted and forbidden ionization states, X-ray and weak radio emission from the nucleus itself, and radio lobes extending from the nucleus on either side of the galaxy producing radio synchrotron radiation [1]. As well, the luminosity of the nucleus is comparable to that of the surrounding galaxy.

Seyfert galaxies can be sorted into two classes by their spectra, often overlapping each other. The nuclei of Class I Seyferts show very broad permitted emission lines (e.g. H I, He I, He II) and narrower forbidden lines (e.g. O III). Doppler broadening is responsible for the breadth of these lines and requires that the hot gas at the source of the permitted lines be moving at speeds between 1000 and 5000 km s$^{-1}$ with respect to the surrounding galaxy. The narrower forbidden lines correspond to gas moving at 500 km s$^{-1}$ [1]. The nucleus of a Class II Seyfert, exhibits only narrow spectral lines of both permitted and forbidden transitions with has Doppler broadening from characteristic rotational speeds of 500 km s$^{-1}$ [1]. Galaxies sharing line width characteristics of both classes are given a fractional class (i.e. 1.5). Class I Seyfert galaxies are typically observed face-on, inclination approximately 0, compared to Class II Seyferts, which are usually found edge-on, inclination approximately 90 [8]. Additionally, the galactic nuclei vary in brightness on timescales of months, requiring them to be less than 1 parsec in diameter [5].

The purpose of these observations is to measure the "blueness" of the dense core of the face-on Seyfert galaxy M77 by subtracting the V band from the B and comparing to the B-V value of a non-Seyfert galaxy with comparable structure (Hubble type) and inclination. The lower the B-V color index, the bluer the object. Coupled with restrictions on the size of the galactic core, these measurements of relative luminosity limit the possibilities in how the galactic core may be structured and whether it can be reasonably deduced to be stellar in composition or not.

Observations

Observations were made using the 24-inch Cassegrain reflector telescope at the C.E.K. Mees Observatory in Rochester, NY with a plate scale of 25 arcsec mm$^{-1}$. The imager was an SBIG ST9XE CCD camera used in conjunction with an SBIG CW8 color filter wheel. The CCD array is 512 pixels square, each 25 m pix$^{-1}$ and 16 bit ADU. This configuration yields a composite image plate scale of 0.5 arcsec pix$^{-1}$, the image then 4.3 arcmin square. The color wheel passbands are 4880-5740 and 3120-5080 for the V and B bands respectively. Flux calibrator stars were chosen based on their uniformity of emission in B and V (preferably spectral type A0 or A1), approximate apparent magnitude as the Seyfert target M77 (9th or 10th mag), and their angular proximity to the Seyfert target (within 5). Consideration was given to angular separation from M77 in choosing the calibrator stars as well as dark sky images in order to maintain consistency in the number of atmospheres we peered through and thus to improve photometry. The stars were imaged in B and V with exposure times sufficient for 25-50 percent full well saturation in ADU counts at the centroids (Table 1).

Table 1 Standard Stars (located on separate sheet)

We chose M77 to be the target Seyfert galaxy as it was one of Seyfert’s originals [2] and as the most luminous and most convenient for viewing at the time of our observations (Figure 1). NGC 772 was chosen as the non-Seyfert counterpart for comparison because of its similar Hubble type and inclination. Both galaxies are unbarred spiral galaxies and oriented largely face-on. By mistake, NGC 779 was observed in place of NGC 772, and the data available for analysis was severely compromised as a result (Figure 2). NGC 779 is weakly barred compared to M77’s lack of any bar, and it is seen nearly edge-on in complete contrast with M77. For M77, four 5-minute exposures in each B and V were taken and for NGC 779, three 5-minute exposures in each B and V (Table 2).

From Figures 1 and 2, there is a very noticeable loss in resolution due to errors in tracking. Short integration times of 5 minutes mitigated the effects of poor tracking, but use of the CCD’s self-guiding camera would have...
All images were reduced using a pipeline consisting of a bias subtraction, a dark sky subtraction, and a dark-subtracted flat fielding. Post-pipeline images were subsequently aligned, rotated, and co-added with attempted hot and cold pixel correction using CCD Soft v.5. Images of dark sky within 5 of M77 and over an exposure time of 5 minutes in B and V were chosen as dark subtracts for the galactic images to compensate for scattered moonlight. At the date of observation, the angular separation from the then three-quarters-full moon was approximately 70. The observations are background limited with a dark sky magnitude of 15.00 ± 0.21 in both B and V for objects of the same angular area as the galactic nuclei of M77 and NGC 779 (5 arcsec diameter). Considering the limiting dark sky magnitude, Table 2 shows that the core of NGC 779 was hardly detectable in our 5-minute exposures with a signal-to-noise ratio of barely 2:1. This is the most compelling reason why a comparison of B-V indices between M77 and NGC 779 from these data is not useful for deducing the structure of the M77 galactic nucleus.

After an image is bias- and dark-subtracted, the flux of a point source is proportional to the integrated sum of its signal in ADUs divided by the integration time. Thus the relative flux of two sources at the same wavelength is given by

\[ \frac{f_1}{f_2} = \frac{ADu_1}{ADu_2} \frac{\Delta t_2}{\Delta t_1} \]

which gives a magnitude difference of,

\[ m_2 = m_1 + 2.5 \times \log \frac{f_1}{f_2} \]

We calculate the fluxes from the reduced images of galactic nuclei using the aperture photometry capabilities of ATV within IDL (Table 2). The only sky subtracted was that background to the galaxy itself; the surrounding galaxy was not subtracted from the nucleus.

**Galactic Nucleus Density**

Comparing the B-V color indices of M77 and NGC 779 from Table 2 is not insightful into the structure of the M77 nucleus. The uncertainty in the color index of NGC 779 overlaps the color index of M77, and the discrepancy between the two galaxies in structure and inclination render them an irrelevant comparison to begin with. NGC 772 is more representative of M77 without its Seyfert nucleus and would provide a better comparison as said in 2.

The B-V color index of the M77 nucleus is below the value 0.91 found by Lokanadham et al. [4], and hence far below that of non-Seyfert galaxies. As a further check, the luminosity of the Seyfert nucleus is often as high as or higher than the luminosity of the rest of the galaxy, which is true for our images of M77. Given that the B-V color

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**FIG. 1:** Class II Seyfert galaxy M77 (NGC 1068) in B band from Mees telescope. Four co-added 5-minute exposures. Observed 10 Oct 2008.

**FIG. 2:** Non-Seyfert galaxy NGC 779 in B band from Mees telescope. Three co-added 5-minute exposures. Observed 10 Oct 2008.
index of the M77 nucleus is very low in the literature, we can deduce limits on its structure. When Seyfert was making his observations in the 1940’s, black holes had not yet been discovered. A bluer color index of a galactic region must correspond to a higher-than-average concentration of bluer and thus hotter and more massive stars. These hotter stars of spectral classes O and B, OB stars, are short-lived on the order of 10 Myr and most often found in star-forming regions. Aside from the nucleus of a Seyfert galaxy, these nurseries of massive stars are the bluest regions of the galaxy. The groups of OB stars, forming in gravitationally unbound collections called OB associations, will be always be found near large expanses of gas clouds undergoing gravitational collapse. A swath just trailing the spiral gravitational density waves emanating away from the galactic core of a spiral galaxy is a prime area of gas cloud collapse, but the galactic core itself is not. There the very high density of stars has consumed and rarefied most of the gas, making it impossible for OB associations to form. Moreover, if an OB association did find itself at the galactic core, the collection would be vastly outnumbered by the cooler, less massive, and thus much longer-lived stars that populate the vicinity of the core. To maintain a low B-V color index for the galactic nucleus, the OB stars would have to be replenished at a physically unrealistic rate on account of their short life span.

Seyfert galaxies are fundamentally different from non-Seyfert galaxies in this respect. Their nuclei are as luminous as the as the entire galaxy, but they are bluer than any physically feasible collection of centrally located OB stars could be. That the nucleus itself is found to be less than 1 parsec in diameter, places additional constraints on any centrally located collection of OB stars. The high density of OB stars necessary to produce the low B-V color index would quickly lead to mass segregation and dispersion, thereby increasing the diameter of the nucleus - contradicting the original condition on the nucleus diameter. This is strong evidence that the central object of the nucleus must be very massive, very dense, and unlike any stars known to Seyfert at the time of his observations.

It would be expected that such a dense, massive, centrally located object in the galactic core would have an accretion disk. Although there would be no ambient gas to supply the disk, the galactic core is so highly populated with stars that many would be torn apart by tidal forces in the vicinity of the massive object. Furthermore, an accretion disk model is supported by the observed Doppler broadening of Seyfert galaxies. At higher inclinations, the observer peers into the disk edge on, and sees a greater difference in velocities of accreting gas moving toward and away from him relative to the surrounding galaxy. This would yield broader emission lines from the hot accretion disk, as found in Class I Seyferts. At lower inclinations, the observer peers down onto the circular accretion disk and sees less discrepancy in the velocities of accreting gas relative to the surrounding galaxy. Consequently, the nucleus exhibits narrower emission lines, as in Class II Seyferts. This model also accounts for why some Seyferts appear as a cross between Class I and Class II - they are likely orientated at some intermediate inclination between 30 and 60. Yet another consequence of the accretion disk model is increased luminosity as the infalling gas converts a portion of its gravitational potential energy and mass energy into light. The dynamics of a supposed massive galactic nucleus of the required density easily skews the spectrum to very high energies. This would account for much of the tremendous luminosity of the nucleus and its low B-V color index.

Much of the theory supporting these deductions was not developed until well after Seyfert first recognized in 1943 the class of galaxies that bears his name [2]. Yet these inferences were at his fingertips, many stemming from the low B-V color index of galaxies such as M77. Had he pursued these connections, he could have predicted the existence of supermassive black holes in the centers of Seyfert galaxies 30 years before their proposal. A theory of supermassive black holes would certainly supply the necessary characteristics as the engine driving active galactic nuclei.

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