Central supermassive black holes in Seyfert galaxies

Spring 2024

In the early 1940s, apparently following up on a suggestion by Milt Humason, Carl Seyfert discovered the class of galaxies with active nuclei that bears his name. The hallmark of a Seyfert galaxy is a relatively bright, starlike central object, easily seen in short exposures, around which long exposures reveal the bulge and disk of a spiral galaxy. Such objects are not present in the vast majority (∼99%) of spiral galaxies. The central object's luminosity is generally within a factor of ten as large as that of the rest of the galaxy, in some cases reaching a large fraction of the galaxy's total luminosity. It is usually very difficult to reconcile the size and luminosity of the central object with the properties of normal stellar clusters. The central object also contains ionized gas for which the emission-line spectrum indicates an ionization state substantially higher than is typical of the HII regions associated with star formation. Profiles of forbidden lines of the ions of "metals" in Seyfert nuclei — by which the ionization state is analyzed — are generally relatively narrow (Doppler velocities of a few hundreds of km/s) and consistent with broadening primarily, but not completely, by the rotation of the galaxy. In Seyferts of type 2, this profile also characterizes the hydrogen recombination lines like Hα and Hβ. In Seyferts of type 1, however, the hydrogen recombination lines have an additional very broad component to their profile that indicates Doppler velocities of a few thousand km/s with respect to the rest of the galaxy, much greater than shown by stellar absorption lines which characterize galactic rotation.

Soon after the discovery of the nature of quasars, it was realized that quasars share many important features of Seyfert nuclei. This led to early predictions that quasars would also turn out to be galaxy nuclei — a prediction borne out shortly after the first CCD cameras enabled precise enough subtraction of the central object to reveal the surrounding galaxy. It also led the astronomical community to regard Seyfert's work as the retrospective discovery of black holes.

Nowaadays, we think that the same basic supermassive-black-hole-plus-accretion-disk geometry applies to both main types of Seyferts, and that the difference between types is an artifact of the angle at which the disk is viewed: we see deeper toward the center of the disk for type 1 than type 2. This suggests that we should also see Seyfert galaxies intermediate in characteristics between these two basic types. This has turned out to be the case, spawning Seyfert classifications like 1.5 or 1.8, in the same spirit as intermediate Hubble morphological classifications (e.g. Sbc or S0/Sa).

In this project, you will repeat some of Seyfert's classic imaging[1] observations, using a CCD camera instead of photographic plates, and demonstrate that Seyfert galaxies each have a starlike, extremely luminous central object which is lacking in most spiral galaxies of the same Hubble type. From this, you can infer some bounds on the properties of the central black holes.

In this project, you will:

- Select a Type 1 Seyfert galaxy, and another galaxy of the same morphological (Hubble) type that is not a Seyfert, taking care that the two are similar in angular size, distance, and inclination. Table 1 contains a good list of type 1 Seyferts. The normal galaxy can be selected from the online Revised Shapley-Ames catalog. You are welcome (and encouraged) to select target(s) that have been previously observed; see the last column in Table 1 and Table 2 for details.

---

[1] Most of Seyfert's 1942 paper is about his spectra of these galaxies, which we will not attempt to reproduce, at least not this semester.

- Take both short- and long-exposure LRGB images of each galaxy, taking careful note of the seeing in each frame by the sizes of stellar images, and making sure that each galaxy's disk and spiral arms are imaged at high signal-to-noise, meaning a magnitude limit of 22–23 for RGB.
- Take long-exposure Hα, [OIII], and [SII] images of each galaxy, making sure that the nuclei and brighter star-formation regions show up well.
- Select and average the images with the very best seeing; from this, prepare color images and one-dimensional plots of G magnitude and B–R color index in each galaxy's nucleus, as a function of distance from the center. Do the same for some of the brighter star-formation regions, highlighted by Hα.
- Average the data in each filter, omitting frames with tracking errors or unusually bad seeing.
- Measure and account for the magnitude limit.
- Carefully edit the data for bad stellar images, deconvolve the L images, and prepare composite tricolor image (LRGB, L-[SII]-Hα-[OIII]) of each galaxy that emphasize the nuclear differences as well as any differences in the disks.

Be sure to address the following in your analysis:

- Do you reach the magnitude limit that you expect? If not, why not?
- Compare the brightness and broadband color of the two galaxies' central bulges. What differences are there? From the colors, are these old or young stellar populations?
- If all has gone well, a bright, unresolved object dominates the center of the Seyfert, which has no counterpart in the normal galaxy. What is the luminosity of this object, and how does it compare to the luminosity of the whole galaxy? What is the maximum diameter of the region in the center of the Seyfert nucleus, from which the object's luminosity emerges?
- What fraction of the broadband fluxes in R, G, and B appear in the narrowband images, for the central object, and for the bulges — outside the central object, for the Seyfert — of the two galaxies? (Note that [OIII] is covered by both B and G, and that both Hα and [SII] are covered in R.) What would be the fraction expected, from the filter bandwidths, for a continuum source? Do you therefore detect the spectral lines in the Seyfert's central object? How about the bulges?
- How does the boradband color of the Seyfert's central object compare to the broadband colors of the large star-formation regions and young massive star clusters in both galaxies?
- Presuming that you have detected spectral lines in the Seyfert's central object: How do [OIII]/Hα and [SII]/Hα in the central object compare to those ratios for the large star-formation regions in both galaxies?
- Can you reproduce the color and luminosity of the central object by summing up emission from stars with a plausible stellar-mass function? If so, what is the stellar density in your hypothetical central cluster, and how frequently do the stars collide?
- Can you reproduce the flux ratios seen in the spectral lines by scaling up a giant HII region? About what spectral type would be required for the exciting stars, presuming that the ionized gas in the Seyfert's central object is photoionized?
- Can you reproduce the color and luminosity of the central object with an accretion disk around a black hole? If so, what are the properties of the disk and black hole?
- In particular: what would be the range of black-hole mass required?
- Can one or other of the models be ruled out from these observations?

Include with your report your best images and plots. Archive these images, and all of your raw and reduced data, on the Astronomy Lab data drive.

Additional reading

Astronomy 142, lectures 17–22

Martin Rees 1984, *ARA&A*, 22, 471

Table 1: Properties of bright northern Seyfert galaxies. Adapted from Lipovetsky et al. (1988).

Name	J2000 coordinates		Redshift	Hubble	Seyfert	B	Aperture	Within aperture:		Previous
	α	δ	z_0	type	type	(total)	[arcmin]	V	B − V	observations
NGC 788	02 01 06.3	-06 48 50	0.0136	S0	2	13		12.76	0.48	
NGC 863	02 14 33.1	-00 46 07	0.0277	Sa	1.5	13.76	1.25	12.96	-0.36	
NGC 931	02 28 14.4	+31 18 47	0.0164	Sbc	1	13.67	2.29	12.78	0.34	
NGC 1068	02 42 40.8	-00 00 48	0.0036	(R)Sb(r)	2	9.17	4.8	8.98	0.08	
NGC 1275	03 19 48.2	+41 30 42	0.0178	S0 pec	1	12.35	2.29	11.62	0.04	
NGC 1667	04 48 36.9	-06 19 12	0.0150	SBc	2	12.75		12.86	0.13	
Mrk 1095	05 16 11.3	-00 08 59	0.0327	S0/Sa	1	13.6	1.25	12.87	-0.62	
NGC 2110	05 52 11.4	-07 27 23	0.0077	SBa(r)	2	13.77	1.25	12.56	0.27	
Mrk 3	06 15 36.0	+71 02 04	0.0141	SB0	2	13.75	1.36	12.66	0.08	
NGC 2273	06 50 08.5	+60 50 45	0.0069	SB0/SBa	2	12.5	2.29	11.92	0.32	
NGC 2639	08 43 38.0	+50 12 20	0.0112	(R)Sa(r)	1	12.65	1.2	11.88	0.39	Mar. 29, 2023 Apr. 20, 2023
NGC 2691	08 54 46.3	+39 32 13	0.0139	SB0/Sba	1	13.76	2.29	12.88	0.26	Mar. 21, 2021 Apr. 26, 2021
NGC 2782	09 14 05.5	+40 06 52	0.0084	Sa pec	1	12.15	1.9	11.77	-0.02	
NGC 2992	09 45 41.7	-14 19 40	0.0073	Sa pec	1.9	13.17	2.29	12.04	0.51	
NGC 3185	10 17 39.4	+21 41 17	0.0038	SBa(r)	1	13.23		12.15		
NGC 3227	10 23 30.6	+19 51 54	0.0033	Sa(r)	1.2	11.55		12.19	0.26	Mar. 20, 2022
NGC 3516	11 06 47.5	+72 34 07	0.0088	(R)SB0/Sba	1	12.45		12.09	0.05	
NGC 3660	11 23 32.6	-08 39 45	0.0115	SBbc(r)	2	12.5		11.90		
NGC 3718	11 32 37.3	+53 04 08	0.0036	SBa pec	1	11.26	6.61	10.61		Mar. 7, 2021
NGC 3786	11 39 42.4	+31 54 35	0.0092	Sa pec	1.8	13.85	2.29	12.49	0.24	
NGC 3884	11 46 13.4	+20 23 06	0.0288	Sa(r)	1	13.79	1.38	12.88	0.4	
NGC 4051	12 03 09.6	+44 31 53	0.0023	Sbc(r)	1	10.95	6.92	10.18	0.02	Mar. 17, 2022 Apr. 12, 2022
NGC 4151	12 10 32.6	+39 24 21	0.0033	(R)Sb	1	11.13	1.07	11.15	-0.47	Mar. 22, 2021 Apr. 26, 2023
NGC 4235	12 17 09.9	+07 11 29	0.0077	Sa(s)	1	12.64	3.39	11.61	0.41	
NGC 4253	12 18 26.7	+29 48 47	0.0128	(R)SB0/SBa	1	13.43	1.25	12.64	0.07	
NGC 4258	12 18 57.5	+47 18 14	0.0020	Sbc(r)	1	8.95	16.6	10.88	0.23	Apr. 10, 2022 Apr. 10, 2023

Table 1: Properties of bright northern Seyfert galaxies. Adapted from Lipovetsky et al. (1988).

Name	J2000 coordinates α	δ	Redshift z_0	Hubble type	Seyfert type	B (total)	Aperture [arcmin]	Within aperture: V	B − V	Previous observations
NGC 4388	12 25 47.1	+12 39 42	0.0082	SBb pec	2	11.83	3.98	11.2	0.15	
NGC 4448	12 28 15.0	+28 37 13	0.0023	S0/Sa	2	12	4.07	11.1	0.42	
NGC 4593	12 39 39.4	-05 20 39	0.0085	(R)SBb	1	11.87	2.29	11.56	-0.02	Apr. 5, 2021
NGC 4594	12 39 59.3	-11 37 23	0.0020	Sa(s)	1	9.27		9.25	0.64	
NGC 4639	12 42 52.5	+13 15 28	0.0030	Sb	1	12.2		12.21		
NGC 4941	13 04 12.5	-05 33 05	0.0029	(R)Sab	2	11.9		11.9		
NGC 4939	13 04 17.7	-10 20 29	0.0098	Sbc(s)	2	12.02	4.37	11.35	0.16	
NGC 5005	13 10 55.9	+37 03 32	0.0036	Sbc(r)	2	10.64	6.46	9.87	0.35	
NGC 5033	13 13 26.7	+36 35 55	0.0032	Sc	1	10.6	9.12	10.16	0.27	Mar. 20, 2021 May 6, 2021
NGC 5273	13 42 08.3	+35 39 16	0.0034	S0(s)	1	12.43	3.39	11.65	0.36	
NGC 5347	13 53 16.9	+33 29 28	0.0079	SBab	2	13.46	2.24	12.7	0.04	
NGC 5363	13 56 07.0	+05 15 19	0.0038	pec	2	11.2	5.5	10.25	0.62	
NGC 5427	14 03 25.9	-06 01 50	0.0083	Sc pec	2	12.05	2.4	11.33	-0.06	
NGC 5506	14 13 14.8	-03 12 27	0.0059	SB0/Sba	2	13.29	2.29	12.54	0.14	
NGC 5548	14 17 59.5	+25 08 12	0.0168	(R)S0/Sa	1.5	13.21	2.29	12.51	-0.42	
NGC 5695	14 37 23.0	+36 34 15	0.0144	SBb	2	13.55	1.25	12.71	0.25	
NGC 5953	15 34 32.3	+15 11 42	0.0075	Sa pec	2	13.1	1.48	12.35	0.21	
NGC 6217	16 32 29.2	+78 11 52	0.0046	(R)Sbc	2	14		11.22	-0.17	
NGC 6814	19 42 40.6	-10 19 24	0.0053	Sbc	1	12.02	2.29	11.54	0.28	
NGC 7469	23 03 15.6	+08 52 26	0.0167	(R)SBa	1	12.6	1.25	12.42	-0.39	
NGC 7674	23 27 57.1	+08 46 49	0.0295	Sbc(r)	2	13.56	1.25	12.98	0.08	
NGC 7743	23 44 21.5	+09 55 58	0.0067	(R)E/S0	2	12.42	2.95	11.43	0.41	

Name	Previous observations
NGC 2844	Mar. 29, 2022
	Apr. 20, 2023
NGC 2880	Mar. 21. 2021
	Apr. 26, 2021
	May 6, 2021
NGC 3180	Apr. 13, 2023
	Apr. 23, 2023
NGC 3310	Mar. 9, 2022
	Mar. 17, 2022
	Apr. 27, 2023
NGC 3351	Mar. 19, 2021
NGC 3593	Mar. 20, 2022
NGC 3898	Mar. 7, 2021
NGC 4145	Mar. 22, 2021
	Apr. 26, 2023
NGC 5055	Mar. 20, 2021
	Apr. 10, 2022
	Apr. 12, 2022
	Apr. 10, 2023
	Apr. 15, 2023
NGC 5194	Apr. 13, 2023
	Apr. 16, 2023
	Apr. 23, 2023

Table 2: Non-Seyfert galaxies for which we have archival data taken at the Mees Observatory.