Physics of Galaxies 2017 10 credits Lecture 6: Active galaxies and black holes



Outline

- Introduction to the database exercise
- Black holes in galaxies
 - How do we find them?
 - Relation between black hole mass and other galaxy properties
- Active galactic nuclei (AGN)
 - Basic AGN anatomy
 - Different types of AGN
 - Unification model
 - Quasar host galaxies
 - Quasar absorption systems

Database exercise





Studying galaxies with the Sloan Digital Sky Survey

Laboratory exercise, Physics of Galaxies, Spring 2017 (Uppsala Universitet)

by

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Deadline June 7 – preferably no more than 5 pages

Obstacles: Astronomical coordinates



Obstacles: Bewildering photometric data

SDSS J113459.47+002509.1

GALAXY ra=173.74782136, dec=0.41921516, ObjId = 588848900446814264

Column names link to glossary entries. Move mouse over a column name to get its units.

| mode | PRIMARY |
|--------------|--|
| status | TARGET PRIMARY OK_STRIPE OK_SCANLINE PSEGMENT RESOLVED OK_RUN GOOD SET |
| <u>flags</u> | STATIONARY MOVED BINNED1 CHILD |
| PrimTarget | TARGET_GALAXY |
| SecTarget | |

| | <u>u</u> | L | g | | <u>r</u> | | i | <u>z</u> |
|------------------|------------|--------------|----------------|---------------|------------------|-------------|-----------------|---------------|
| – <u>5</u> " N – | 19. | 55 | 18.04 | | 17.55 | | 17.35 | 17.21 |
| | err | <u>u</u> | <u>err_g</u> | L | <u>err_r</u> | | <u>err_i</u> | <u>err_z</u> |
| | 0.0 | 03 | 0.01 | | 0.01 | | 0.01 | 0.02 |
| E W | <u>run</u> | <u>rerun</u> | car | ncol | field | <u>obj</u> | rowc | <u>colc</u> |
| | 756 | 44 | | 4 | 387 | 56 | 549.4 | 1974.6 |
| 12000 | fiberMa | ag_r pet | <u>roMag_r</u> | <u>devMag</u> | <u>g_r expMa</u> | <u>ag_r</u> | <u>psfMag_r</u> | modelMag_r |
| | 18.0 | 5 | 17.55 | 17.55 | 5 17.5 | 5 | 17.99 | 17.55 |
| - s - | extin | ction_r | petrol | Rad_r | | pare | entid | <u>nChild</u> |
| | 0 | .06 | 1.7 | '96 | 58884 | 8900 | 446814263 | 0 |

Register an account!



SQL (Structured Query Language)

| 17 | SDSS Query / CasJobs | | |
|------------------|---|------------------------------------|----------------------------------|
| Help Tools | s Query History MyDB Import Groups Outpu | ut Profile Queues SkyServer Logout | beatriz.villarroel.rodriguez@gma |
| Context | Table (optional) Task Name | | |
| DR7 | somecoolname somecoolname | | |
| Samples Re | cent Clear | | Syntax Plan Quick Submit |
| 1 select | S.bestobjID objectID, S.z redshift | | Submits y |
| 3 4 5 6 | from SpecObj S | | |
| 7 8 | where S.z > 0 AND S.z <1 AND (S.specclass=3 OR | <pre>specClass=4)</pre> | |

Fig.6. The Casjobs Query interface. Write your SQL code for selecting your favourite objects here.

Connection to your essay

Finally, I'd like you to reconnect this exercise to the **topic of your written essay or a specific research problem described in it**. Many research problems can be solved using the SDSS and sometimes one only has to figure out a clever way to approach them. Other times, even if one cannot solve the problem using the SDSS directly, the survey is helpful for e.g. selecting interesting candidate objects.

Exercise 4: (a) Describe the most interesting research problem from the essay very briefly.

(b) How could you approach this fascinating research problem using the SDSS? If it is not possible to use the SDSS, explain what the solution requires that cannot be met by the SDSS data.

Problems with the instructions?

- Recent updates to the SDSS interface could potentially cause problems with some of tasks that you are asked to perform as part of this exercise
- If this happens just add a "bug report" section to your report and explain what the problem was

Black holes



Non-rotating black hole Rotating black hole Current observational evidence supports the existence of stellar-mass black holes (~10 M_{\odot}) and supermassive black holes (~10⁶-10¹⁰ M_{\odot}). The evidence for intermediate-mass black holes (~ 10²-10⁵ M_{\odot}) remains scant

Hunting down black holes

Motion of stars

- Milky Way: Proper motion of indivdual stars
- Other galaxies velocity distribution from integrated stellar population spectrum
- Active galactic nuclei
- Gravitational waves
- •X-ray binaries
- Ultraluminous X-ray sources
- Gravitational lensing

The black hole at the centre of the Milky Way

Milky Way: M_{BH}≈4×10⁶ M_☉



Relation between black hole mass and stellar velocity dispersion (or mass) of bulge



 $M_{\underline{\text{SMBH}}} \sim 0.002$ MBulge

Supermassive black holes in AGN

- Doppler broadened emission lines in AGN indicate gas velocities ~ 10 000 km/s
- Line variability time scale (weeks) → size of lineemitting region
- Velocity & size → Mass(<size) & Density, indicating that the gas orbits a SMBH

Schwarzschild radius:

$$R_{\rm S} = \frac{2GM_{\rm BH}}{c^2} \approx 3 \times \frac{M_{\rm BH}}{M_{\rm solar}} \,\mathrm{km}$$

Characteristics of Active Galactic Nuclei

- High luminosity produced in small regionFast variability
- High fraction of polarized light
- •Non-thermal spectrum: Not stars!
 - Synchrotron radiation
 - Emission-line ratios
 — Ionization source more energetic than hottest known stars

Intermission: Music from AGN



Dr Fiorella Terenzi Music from the Galaxies (1991): Radio waves from the active galaxy UGC 6697 converted into music

Intermission: Music from AGN



<u>NGC 4151 (1993):</u>

Rest-frame UV emission-line and continuum variability from the Seyfert galaxy NGC 4151 converted into music

Professor Nils Bergvall

Variability-Size Relation

- Fast variability indicates that the luminosity is produced inside a small region
- Light variations on scales down to 1 hour → size smaller than the Solar system



Accretion Disks



Magnetic field channel matter into relativistic jets

SMBH

Angular momentum of infalling material→ matter spirals inward in an accretion disk

Eddington Luminosity

Too high radiation pressure of AGN may overcome inward gravitational force → upper limit on AGN luminosity which still allows material to fall inwards



Note: L_E assumes spherical accretion. Super-Eddington luminosities (a few times L_E) can be produced in accretion disks

Radiation Efficiency

- Mass M falling into a SMBH→ energy Mc² added
- Theoretical maximum:
 - 42% of Mc² is converted into luminosity
 - The rest increases the SMBH mass
- But typically, ≤10% of Mc² is converted into luminosity
- SMBHs in a typical quasar grows with \geq 1 M_{solar}/yr
- Activity is expected to last for ~ 100 Myr \rightarrow $M_{SMBH} \ge 10^8 M_{solar}$ in faded quasars

The Central Power Source



Transitions and Line Profiles

- Forbidden lines (e.g. [OII]3727Å, [OIII]5007) originate in lowdensity gas (n_H≤10⁸ atoms/cm³)
- Allowed lines (e.g. H α , H β) originate in more dense gas
- Broad lines, $\Delta v \sim 10000 \text{ km/s} \text{Allowed}$ (originate close to the nucleus, in dense medium)
- Narrow lines, $\Delta v < 1000 \text{ km/s} \text{Forbidden}$ (originate further out, in less dense medium)





Jets and Lobes



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Intermission: What is happening here?



Synchrotron Radiation

- Relativistic electrons spiralling around magnetic field lines
- B=1-10 µG in lobes (same as B close to the Sun)
- B=0.1 G in active cores



Power-Law Spectrum

$$f_{\nu} \propto \nu^{-lpha}$$

- •In radio, due to synchrotron radiation: $\alpha = 0.7 - 1.2$
- In optical, probably caused by thermal radiation from the accretion disk:

α=0-2

Superluminal motion

Blobs appear to move outwards at 5-500 What's going on?



Superluminal motion



Observer

 $\mathbf{v} \approx \mathbf{c} \rightarrow \mathbf{v}_{ob}$

 $\Delta t_{\rm obs} = \Delta t (1 - (v/c)\cos\theta)$

In Δt_{obs} , the blob travels v $\Delta t \sin \theta$ across the sky, With apparent velocity v_{obs} :

$$v_{\rm obs} = \frac{v\sin\theta}{1 - (v/c)\cos\theta}$$

The number densities of AGN at z=o

Type Spiral galaxies E/So galaxies Number/Gpc³ ~5×10⁶ ~ 1×10⁶

Seyfert galaxies $\sim 1 \times 10^5$ Radio galaxies $\sim 3 \times 10^3$ Quasars ~ 100 Blazars ~ 80

Quasars

•Originally: • Quasar = "Quasi-stellar radio source" (radioloud) • QSO = "Quasi-stellar object" (radio-quiet) •Today: Quasar = Both types



Quasars

 Most luminous of the non-transient objects in the Universe: M_{B} <-23 Radio-quiet quasars >10 times more common than radio loud ones Both broad and narrow lines



X-ray quasar with jet

Seyfert Galaxies

Galaxy NGC 7742



PRC98-28 • Space Telescope Science Institute • Hubble Heritage Team

Seyfert Galaxies

• "Low-luminosity quasars" • Almost always in S- or So-galaxies Seyfert 1 nuclei Broad lines (allowed) & Narrow lines (forbidden) High optical luminosity Seyfert 2 nuclei Narrow lines only, but with wings Low optical luminosity

LINERs

- LINER = Low Ionization Nuclear Emission Line Region
- Low luminosities (lower than Seyfert 2)
- Exhibit lines which do not require very energetic power sources – hot stars sufficient
- Many LINERs are probably starbursts, not genuine AGN

Radio Galaxies

- Milky Way: 10³⁰ W in radio
- Radio galaxies $\geq 10^{34}$ W in radio
- Lobes and hot spotsAlways elliptical galaxies



Blazars

- The most rapid and large variations among AGN
- Originally:
 - BL Lac (very weak emission lines)
 - OVV = Optically violent variable (strong emission lines)
- Today: Blazar = BL Lac & OVVs
- Appear to be the most luminous objects in the Universe, but this is due to beaming
- Often completely featureless spectrum
 - Emission-lines weak or absent

Intermission: What sort of AGN is this?



Optical spectrum reveals lots of narrow emission lines

Intermission: What sort of AGN is this?



The Unification Model



Radio galaxy



Quasar Host Galaxies



- The AGN of a quasars typically outshines its host galaxy
- To study the host galaxy, one utilizes the fact that the AGN is a point source wheras the host is an extended object

Quasar Host Galaxies

• Point spread function (PSF): Describes how the light of a perfect point source is distributed on the detector (CCD) because of telescope imperfections, diffraction etc.



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Cosmological Evolution



- At z≈3, bright quasars appear ~1000 times more common than today
- Quasar activity drops at even higher redshifts
- The highest-redshift quasar detected so far has z≈7
- Very challenging to build a SMBH by z=7 (less than 1 Gyr after the Big Bang) – exotic formation channel required?



Damped Lyman-Alpha Clouds

- Dense, neutral gas $N(HI) \approx 2 \times 10^{20} \text{ cm}^{-2}$
- Often interpreted as gas associated with intervening galaxies
- Many DLAs are also Lyman-limit systems



Lyman-Limit Systems

• Dense, neutral gas

• Absorbs hydrogen-ionizing radiation at $\lambda < 912(1+z_{LLS})$ Å



Identifying the Absorber



Quasar 2 3 4

1

Wavelength

The Lyman-Alpha Forest

- Low-density, very extended clouds in the intergalactic medium
- Proximity effect:
 - Ly α -forest thinner at $z_{abs} \approx z_{OSO}$
 - Indicates that clouds close to the quasar are photoionized by it



The Gunn-Peterson Test

- If the Universe (the intergalactic medium, IGM) is neutral at z_{QSO} , then a strong absorption feature blueward of Ly α in quasars should appear – *the Gunn-Peterson trough*.
- This does indeed appear at z_{QSO}≈6, indicating that the transition from an neutral to ionized IGM takes place at around this redshift

Universe ionized at z_{QSO}



Universe neutral at z_{OSO}



Wavelength

Wavelength