9. EXTRAGALACTIC ASTRONOMY

Astro Lab Landessternwarte Königstuhl
Jochen Heidt & David Hiriart

February 23, 2023

Abstract

Our view on how galaxies form and evolve has changed dramatically with the Hubble Deep Field. In 1996 was took the deepest image of a small region on the sky ever taken. It has shown that galaxies in the past (look–back time approx. 10 billion years) had a substantially different morphological appearance than the galaxies today. At the same time, QSO were detected at largest redshifts (look–back time approx. 13 billion years) using the Sloan Digital Sky Survey giving evidence that supermassive black holes are an important ingredient in galaxy formation and evolution.

The task Galaxies & QSO is divided in three parts. In part one, about 80 galaxies in the Virgo cluster are morphologically classified by eye and using this information some properties of the Virgo cluster as well as galaxy transformation mechanisms will be derived.

The comparison of the morphological properties of galaxies in the Virgo cluster to the one of field galaxies and galaxies in the Local Group can be interpreted in terms of luminosity functions. The comparison to the Hubble Deep Field allows further to develop evolutionary models for galaxies. Armed with that knowledge the Galaxy Zoo project will be introduced and actively be participated in part two. The Galaxy Zoo project is an international collaboration of about 20000 volunteers, who classify by eye millions of galaxies morphologically (better than a software can do!). Using this enormous amount of information statistical tests can be used to probe models of galaxy formation. Finally, in part three, an introduction to the world of Quasi Stellar Objects (QSO) is offered. This includes determination of a redshift of a QSO using emission lines, estimate of luminosities and comparison to inactive galaxies, interpretation of broad–band spectra, luminosity function and its Malmquist Bias within as well as apparent superluminal motion. The aim of this task is to introduce to some fundamental properties of galaxies and QSO. and is offered for Master– and PhD–students. It can also be done by Bachelor–students provided that they have attended the lecture Introduction into astronomy & astrophysics I and II.

1 Classification of galaxies in the Virgo cluster.

Material.

1. Palomar Observatory Sky Survey (POSS) plate of the Virgo cluster.
2. Sloan Digital Sky Survey (SDSS) DR10 Finding Char Tool 12^h 30^m +12°
3. Hubble Atlas of Galaxies
4. Images of the Hubble Deep Field North (HDF–N) or you can look better pictures from the Internet.

Tasks

1. Classify the galaxies of POSS plate by using their coordinates provided in Tables 1 and 2 according to the Hubble classification–scheme. Get first familiar with galaxy types by inspecting the Hubble Atlas of galaxies. Then, get familiar with the SDSS skyserver tool available at

   http://skyserver.sdss3.org/dr10/en/tools/chart/chartinfo.aspx

   and find out what you can set as parameters and additional options. Start with RA 187.73961 and Dec 11.46850, set the scale at 30"/pix, width to 1024 pix. It shows to you the same field as provided as material separately. Further information about some objects can be found withe the Navigate Tool by clicking on the object (not every object has additional information). Those may help you to classify the galaxies. Use the provided material to mark the targets with their identification into Hubble type based on the inspection of the galaxies using the SDSS skyserver tool.

2. Present the frequency distribution of the different types in a histogram with E0, E3, E7, S0/SB0, Sa/SBa, Sb/SBb, Sc/SBc, and Irr. galaxies on the abscissa.
3. Compare the apparent frequency distribution with the one for the bright field galaxies and among the members of the "Local Group" and interpret the difference with the luminosity function of galaxies.
4. Can the distribution of ellipticities of the E–galaxies be explained by a homogeneous population of oblate spheroid with constant axes ratio?
5. The center of the Virgo cluster is near the giant elliptical galaxy M86 = NGC4406. Identify M86 with the help of the "Hubble Atlas" and compare the relative frequency of

   $$\frac{\text{E+S0}}{\text{S+SB+Irr}} \quad \text{and} \quad \frac{\text{SB}}{\text{S}}$$

   within and outside radius of 75 arc-min around the center. Here you can use your material with galaxies classified. To which physical radius does this correspond? Interpret the ratios.

6. Which processes lead to the differences found in 3 and 5? Which galaxy morphology do you expect for extrapolation to high redshift?

   In December 1995 a special region on the sky was exposed very long by the Hubble Space Telescope. This region is now known as the Hubble Deep Field North (HDF–N). Almost all objects visible are extragalactic and redshifts $z > 1$. Which morphology is dominating? Does this correspond to your expectations?

Hints

1. Get familiar with the Hubble classification scheme of galaxies with the images in the "Hubble Atlas of Galaxies" and by using the literature.

   Note: Try to avoid mistakes when classifying. These mistakes may result from the changing appearance of each spiral type depending on inclination and scale.

2. Distinguish the SB–galaxies from the S–galaxies in the histogram by hatching the part of the SB–galaxies.

3. Compare your results with the following distributions (dE = Dwarf elliptical galaxies; dSp = Dwarf spheroidal galaxies).

	E	S0	SB0	Sa	Sb	Sc	SBa	SBb	SBc	Irr	dE, dSph
Field galaxies	10%	8%	4%	7%	17%	30%	3%	6%	2%	3%	10%
"Local Group"	2%	–	–	4%	2%	–	–	2%	–	27%	69%

4. How is the ellipticity class defined? How is connected to the intrinsic axes ratio of an oblate spheroid? Assume an isotropic distribution of the orientation.

5. The Virgo cluster is assumed to be at a distance of 20 Mpc. How large is the "Local Group"?

6. The HDF–N contains about 3000 galaxies and around 8 stars. Choose an area of a few square centimeter and qualitatively classify the objects.

Literature

Hubble Atlas of Galaxies (Introduction)
Baschek, Unsöld "Der neue Kosmos"

Table 1: Galaxies in the Virgo cluster.

Nr.	RA	Dec
1	184.93689	12.81077
2	185.31860	11.51378
3	185.65578	11.80447
4	185.82175	11.36756
5	185.66610	9.33683
6	185.50649	9.04034
7	186.05269	8.52671
8	186.00400	12.19912
9	186.26642	12.88713
10	186.38554	12.24746
11	186.23097	11.70423
12	186.33798	10.00714
13	186.43233	12.66298
14	186.52416	13.11340
15	186.41175	12.80478
16	186.54066	12.94347
17	186.63435	12.61065
18	186.72041	9.57815
19	186.79224	9.43637
20	186.62193	8.87405
21	187.56812	13.57062
22	187.06806	9.43048
23	187.00269	9.80266
24	186.86821	11.10574
25	186.91863	13.07901
26	186.9379	12.99276
27	186.80082	12.72554
28	186.97133	12.29731
29	187.18045	11.75504
30	187.24842	13.24744
31	187.26253	13.18381
32	187.24649	13.97162
33	187.47004	14.05589
34	187.50912	13.63656
35	187.45045	13.42233
36	187.49380	12.34689
37	187.56683	12.31592
38	187.70416	12.38714
39	187.73961	11.46850
40	187.53063	10.77670

Table 2: Galaxies in the Virgo cluster (Cont).

Nr.	RA	Dec
41	187.36474	8.73937
42	187.70745	8.35135
43	187.66335	8.99338
44	188.16849	14.05085
45	188.04481	13.40868
46	187.88364	11.60630
47	188.01916	11.17156
48	188.56840	13.06241
49	188.58571	10.92110
50	188.41132	9.16767
51	188.36808	8.65111
52	188.57183	8.20873
53	189.23593	14.21153
54	189.18005	13.2537
55	189.20937	13.15511
56	188.90894	12.54911
57	188.87355	12.20973
58	189.10599	11.44171
59	189.43138	11.81820
60	189.37734	9.55507
61	189.97538	10.17464
62	190.29906	10.15499
63	190.24496	11.90346
64	190.30112	11.88488
65	190.5012	11.65021
66	190.71821	13.25736
67	190.97433	13.13728
68	190.8744	11.58683
69	190.91003	11.55866
70	186.46051	10.45331
71	186.00354	11.22499
72	185.51745	12.74474
73	185.51711	12.78749
74	190.53451	12.59951
75	188.66327	11.29214
76	188.05923	10.25144
77	189.13837	11.25613
78	189.13837	11.25613
79	186.68631	8.88245

2 The Galaxy Zoo

After you have learned in Task 9.1 to classify galaxies and how they are distributed as a function of the environment its now time for some real science and for fun!

The Sloan Digital Sky Survey (SDSS) is the most ambiguous and certainly the most successful sky survey ever undertaken. In principle, it is a successor of the Palomar Observatory Sky Survey (POSS), which you just have used in the previous task. A spin–off of the SDSS was the “Galaxy Zoo Project” during the course of which millions of galaxies in the SDSS data base were morphologically classified by eye by volunteers worldwide. This resulted in a huge data base for morphological studies of galaxies via statistical methods.

Since the project was so successful, it has now been expanded to another huge source of information: the Dark Energy Camera Legacy Survey (DECaLS). Because it uses a larger telescope, DECaLS is 10 times more sensitive to light than the survey that supplied images to the first iteration of Galaxy Zoo, the Sloan Digital Sky Survey. That means that we can see more detail. In this task, you will get familiar a bit with the SDSS, learn details of the Zoo Project, go through a tutorial and finally participate actively in the exciting “Galaxy Zoo” project.

Tasks

1. Using a Web browser go to the SDSS home page (www.sdss.org) and get familiar with it. What is the meaning of SDSS I and SDSS II? How was the photometry done in the SDSS I? Which filter set was used for the photometry?

2. Go now to the Galaxy Zoo Project (https://www.galaxyzoo.org), then read about the science to be undertaken “learn more”. Go back, and continue with “get started”, go through the tutorial and then start right away with your classification. In order to actively take part and your results being saved, you need to log-in (or sign-in) with the UID: jheidt and PW: try2deep before. Enjoy yourself by classifying 20-30 galaxies

3. Finally, logout

3 Quasars and cosmology

Tasks

1. What is the 3C catalogue? When were the quasars discovered?

2. Compare the positions of the Balmer lines of 3C 273 with the positions of the laboratory spectrum. Determine the plate scale with the laboratory spectrum and then the redshift z of the Balmer lines of 3C 273 (Figure 1) How large is the Doppler velocity?

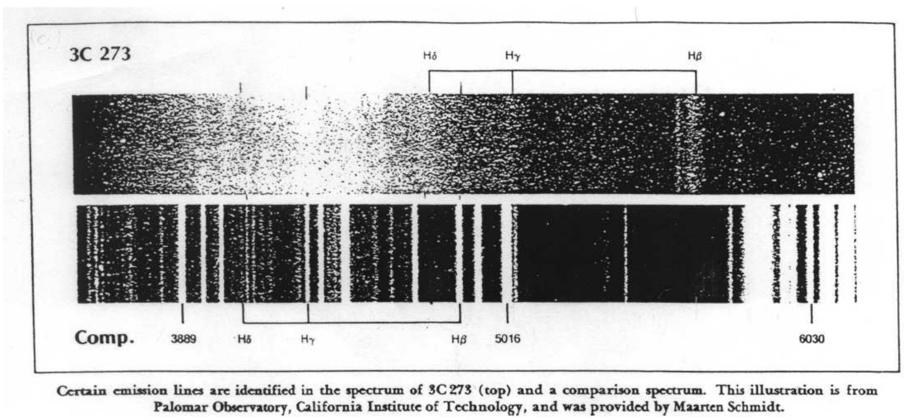

Figure 1: Optical spectrum of 3C 273 (*top*) and a comparison spectrum (*bottom*).

3. What is the Hubble law? Determine the distance of 3C 273 from the Hubble law. Determine the length of the jet of 3C 273 on the B–band image in Figure 2 with the reference stars given in Table 3.

   What is the physical length of this jet? What is the physical dimension of the underlying galaxy (assume the black part of the 3C 273 image to be the host galaxy)?

Table 3: Reference positions near 3C 273.

Name	Right Ascension	Declination
3C 273	$12^h26^m33.25^s$	2°19'43.3"
Star G	$12^h26^m29.77^s$	2°19'53.3"
Star X	$12^h26^m34.41^s$	2°20'10.5"
Star B	$12^h26^m29.40^s$	2°18'51.1"

4. Quasars were proven up to a redshifts of $z > 6$. Is the Hubble law also correct for quasars with a redshifts of $Z = 4$? Which relation applies between angular

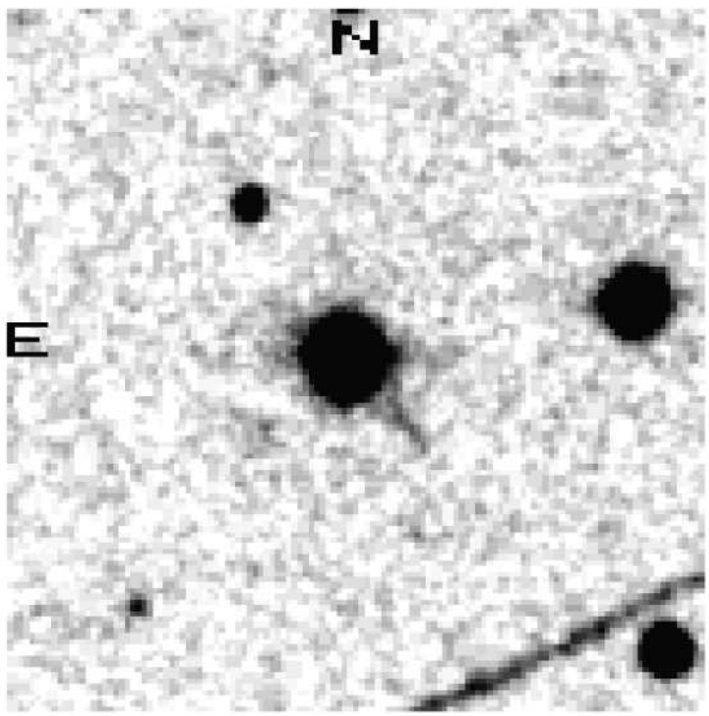

Figure 2: B–band image of 3C 273.

diameter and physical diameter of 30 kpc (spiral galaxy) at a redshift of $z = 2$ on optical images? What is the apparent magnitude of such a galaxy (use the absolute magnitude of the Milky Way as example)?

5. Determine the absolute magnitude of 3C 273 from the distance and the apparent magnitude. How this compare to the absolute magnitude of a Schechter luminosity function–galaxy? Compare your result with the absolute magnitude of optically selected quasars in Figure 3.

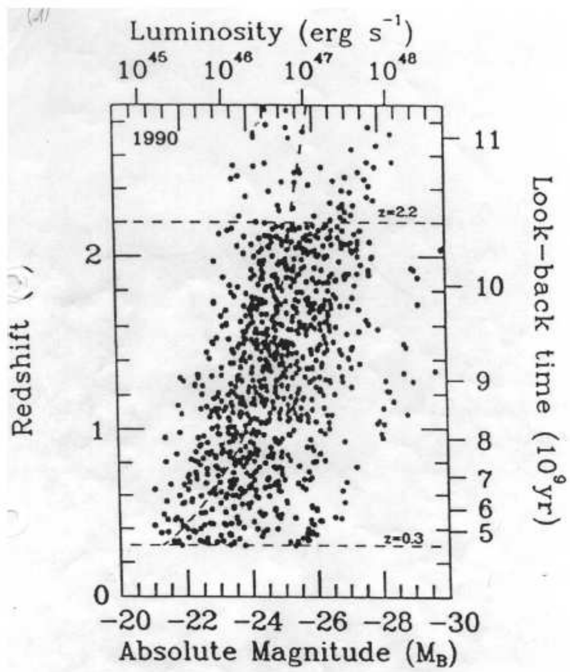

Figure 3: Absolute magnitude and luminosity of optically selected Quasars.

6. Determine the maximal dimension of the emission line region responsible for the fastest variations in the 3C 273 light curve in Figure 4.

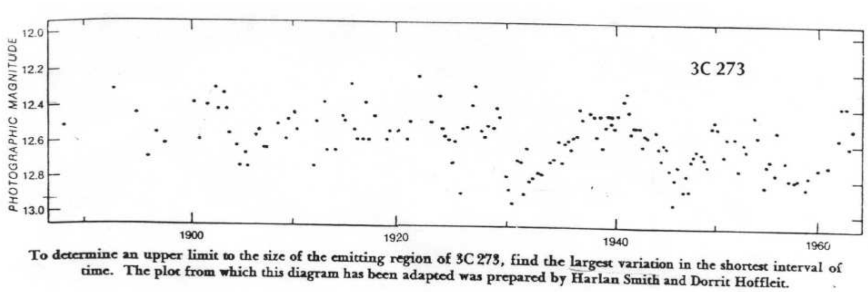

Figure 4: Light curve of 3C 273.

7. Compare the distribution of the continuum energy of 3C 273 with the Milky Way and IR–galaxy spectra in Figure 5. What is the UV bump of a quasar? Discussion: Why do we graph λF_λ vs $\log(\lambda)$ instead of F_λ vs $\log(\lambda)$.

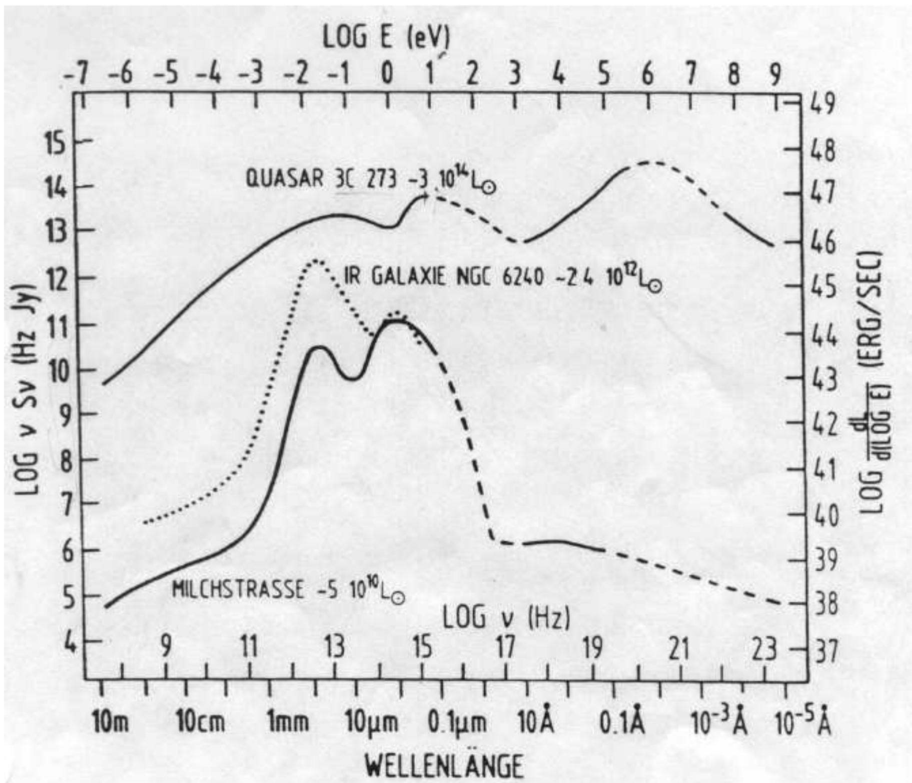

Figure 5: Spectral energy distribution of 3C 273, the Milky Way, and an IR–galaxy.

8. What is VLBI? VLBI maps of 3C 273 in Figure 6 show knots of emission, which move away from the core over the years. Determine the angular velocity in milliarcseconds per year (mas yr^{-1}) from the VLBI map and convert the result in absolute expansion velocity $v_\perp$ and then interpret your result. When was the superluminal motion phenomenon discovered for the first time?

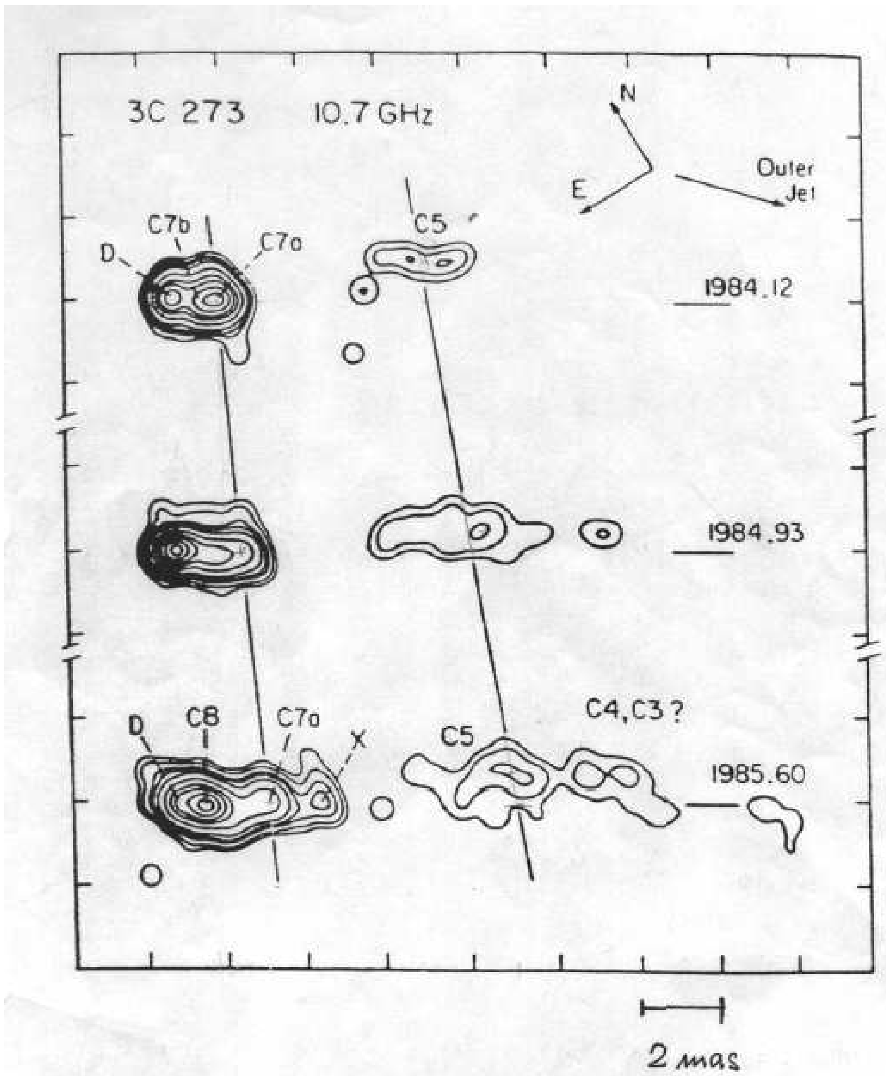

Figure 6: Superluminal motion in the jet components of 3C 273. The diagonal lines represent fits to the proper motions of the centroids of knots C5 and C7a of the jet relative to the core (Cohen, M.H. et al. 1987, ApJ, 315, L89).

Hints

to d) The linear Hubble relation $d(z) = cz$ is not valid for redshifts $z > 0.1$. From cosmology, the relation is

$$d(z) = \frac{c}{H_0} \frac{2}{\Omega^2} \left(\Omega z + (\Omega - 2) \left(\sqrt{1 + \Omega z} - 1 \right) \right) \quad \Lambda = 0 \quad . \tag{1}$$

There results a generalized relation between the physical diameter and the angular diameter Θ of an object

$$\Theta = (1 + z)^2 \frac{D}{d(z)} \quad . \tag{2}$$

So for $z > 1$ the angular diameter is nearly independent of z. This is an important property of the expanding universe (Figure 7).

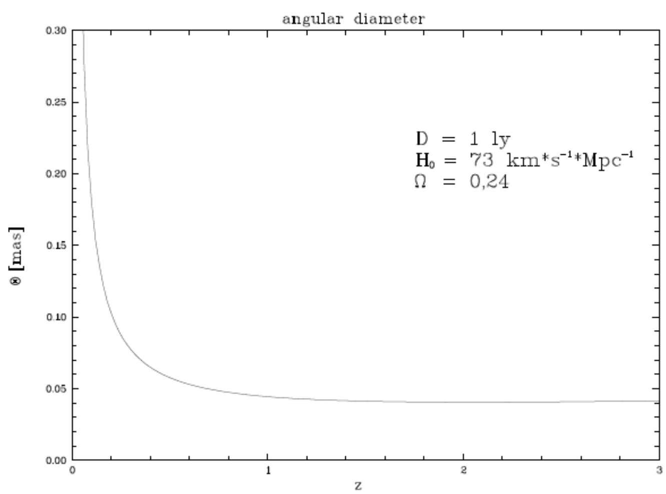

Figure 7: $\Theta(z)$ vs. z according to eq.(2) with parameters D, H_0, and Ω.

to e) Quasars are not standard candles. There is a broad distribution of the absolute magnitude at a given redshift. The luminosities range typically from 10^{45} to 10^{48} ergs s^{-1}, i.e. they are easily brighter than their host galaxy. Thermal emission cannot be higher than Eddington luminosity. Hence, the derived optical luminosity give a lower limit for the central masses of quasars.

to f) Results of the dimension of an emission line region come from the typical time scales on which radiation varies. Because of the finite speed of light the dimension R of the region is limited to $R < c\Delta t$ where Δt is the characteristic fluctuation time scale.

to g) The energy distribution of 3C 273 shows three maxima: one in the infrared, in the UV, and in the X–ray (E>100keV). The radio–infrared radiation is synchrotron radiation, the UV bump forms from emission on an accretion disk around a black hole with mass of 10^9 to 10^{10} $M_\odot$. The exact energy distribution in the UV and X regions is not known. The hard X–ray and the Gamma emission come probably from inverse Compton scattering of the UV photons on relativistic electrons. This radiation is completely absent in normal galaxies.

to h) The measured angular velocity $\dot{\Theta}$ is converted to the transversal velocity $v_\perp$ by the formula

$$v_\perp = \dot{\Theta} \frac{d(z)}{1+z} \quad . \tag{3}$$

There are velocities $v_\perp > c$ possible! The apparent superluminal expansion results from the knots emission which move in the jet close to the speed of light $v_k = \beta_k c$ under a small angle i to the line of sight (special relativistic effect, see Figure 8).

$$v_\perp = c \frac{\beta_k \ \sin}{1 - \beta_k \cos \ i} \quad . \tag{4}$$

Discuss this transversal expansion velocity $v_\perp$ as a function of the angle i for different values of the Lorentz factor $\gamma_k = (1 - \beta_k^2)^{-1/2}$.

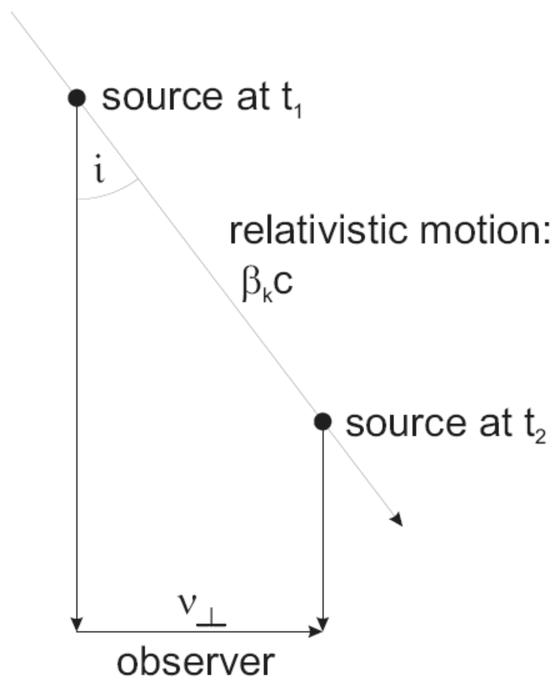

Figure 8: Superluminal motion.