9. EXTRAGALACTIC ASTRONOMY

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March 4, 2024

Abstract

Our view on how galaxies form and evolve has changed dramatically with the Hubble Deep Field. It was observed in 1996 and was the deepest image of a small region on the sky ever taken at that time. It has shown that galaxies in the past (look–back time approx. 10 billion years = redshifts $z \approx$ 2-3) 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 = redshifts $z \approx 6$) 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 QSOs. It 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.

1. In this part you will (try to) classify 78 galaxies in the Virgo cluster based on their morphological appearance. To start with, you should recall the Hubble fork diagram and familiarize yourself with individual members of it by inspecting examples at this page. Once done, classify the 78 galaxies shown here.

   The images are drawn from the Sloan Digital Sky Survey (SDSS). Underneath of each of the images you will find a link to the corresponding Navigate Tool for the SDSS, where you can find more information (e.g. spectra) for most of the sources. They may help you to classify the galaxies. Make only a rough classification into E0, E3, E7, S0/SB0, Sa/SBa, Sb/SBb, Sc/SBc, and Irr galaxies. Be careful when you classify as projection effects (inclination) may lead to misleading results particularly for spiral galaxies. On the other hand, don't worry about having a false identification rate of 20% or so. Most automatic classification tools - even machine learning based ones - will hardly be more accurate.

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

3. Table 1 gives the distribution of galaxy types in the Local Group and of field galaxies (dE = Dwarf elliptical galaxies; dSp = Dwarf spheroidal galaxies, which we did not count for the Virgo cluster here). What are the main differences between the percentages in the Virgo cluster, the field and local galaxies? Galaxy numbers in any environment can be counted as a function of luminosity bins. This is often referred to as a Schechter luminosity function. A Schechter luminosity function is given by a power law with an exponential cut-off at high luminosity and is defined as:

$$dn(L) = \phi dL = \phi^* (\frac{L}{L^*})^\alpha \, e^{-\frac{L}{L^*}} \, d(\frac{L}{L^*}) \qquad (1)$$

   The luminosity L^*, where the power-law turns into an exponential cut-off, is a characteristical luminosity. In galaxy evolution studies galaxy luminosities are often given in units of L^*.

   Describe the Schechter luminosity function for the local galaxies and interpret the results in terms of luminosity function as a function of the environment in which the galaxies reside.

	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%

Table 1: Distribution of galaxy types in the loal group and the field.

4. Can the distribution of ellipticities of the E–galaxies be explained by a homogeneous population of oblate spheroids with a constant axes ratio? Describe qualitatively your answer and the reason why.

5. The center of the Virgo cluster is near the giant elliptical galaxy M86 = NGC4406. A large portion of the Virgo cluster is shown in this image. In this image the location of the 78 galaxies which you just identified are marked. You will there find also a red circle indicating the central part of the Virgo cluster with a radius of 75'. This circle contains 24 galaxies you just classified, namely the ones with the obj-IDs. 8,9,10,11,13,14,15,16,17,21,25,26,27,28,30,31,32,34,35,36,37,38,72,73. Compare the relative frequency of

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

   within and outside a radius of 75' around the center. To which physical radius does this correspond? Assume a distance of 20 Mpc for the Virgo cluster. Interpret the ratios.

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

   Following on the enormous success of the Hubble Deep Field taken in 1995, an even deeper image was acquired in 2003 and 2004 known as the Hubble Ultra Deep Field (HUDF). It contains about 10000 mostly very distant galaxies with redshifts $z > 1$. Inspect a zoomable version of the HUDF. Which morphology is dominating? Does this correspond to your expectations?

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) which you have just used is the most ambiguous and certainly the most successful sky survey undertaken (altough there are now a few more like the LSST-project). It is in principle the successor of the Palomar Observatory Sky Survey (POSS). 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.

This project lead to the foundation of "citizen sicence". Since it was so successful, it has been expanded to many different branches and is now dubbed "Zooniverse". The Galaxy Zoo project as part of the Zooniverse is still in operation, but has been shifted to more recent data sets. At present you are asked to actively investigate images from the James Webb Space Telescope (JWST)!

In this task, you will get familiar a bit with the SDSS, learn more about Zooniverse and 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 - V? 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 as many galaxies as you wish. You are also welcome to check out some of the other Zooniverse projects.

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?

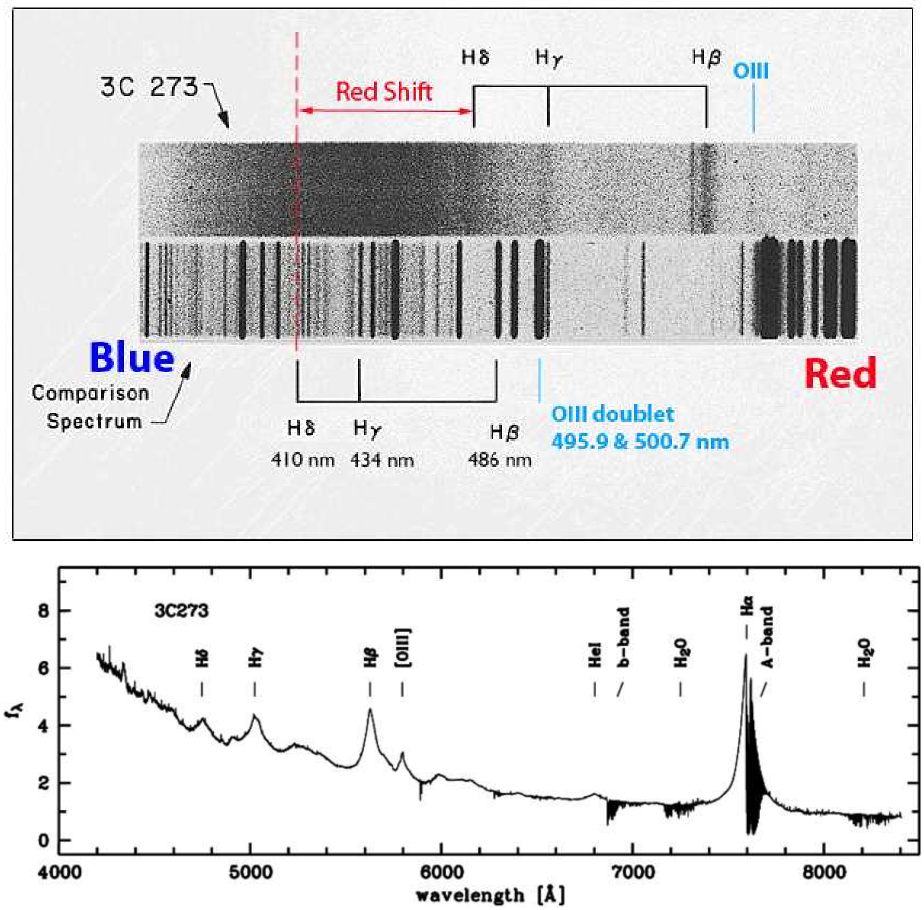

Figure 1: Top: Optical spectrum of 3C 273 which was used by Maarten Schmidt in 1962 to determine the redshift of 3C 273 the first time. Bottom: A more modern spectrum of 3C 273.

3. **Optional:** If you wish, you can determine the redshift of 3C 273 more accurately by using the Lyα-line as observed by the International Ultraviolet Ex-

plorer (IUE). You will do that by using the VO tool SPLAT (SPectraL Analysis Tool). Just follow the instructions in the script splat_redshift.pdf. available on the AstrolabWEB. There you will also find the splat-vo jar-file which you need to download on your laptop to run SPLAT. To run Splot type:

java -jar splat-vo-3.15_1.jar

4. 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 2.

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

Table 2: 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”

5. Quasars were proven up to a redshifts of $z > 6$. Is the Hubble law also correct for quasars with a redshifts of $z = 4$? What is the angular diameter in arcseconds of a galaxy 30kpc in size 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)?

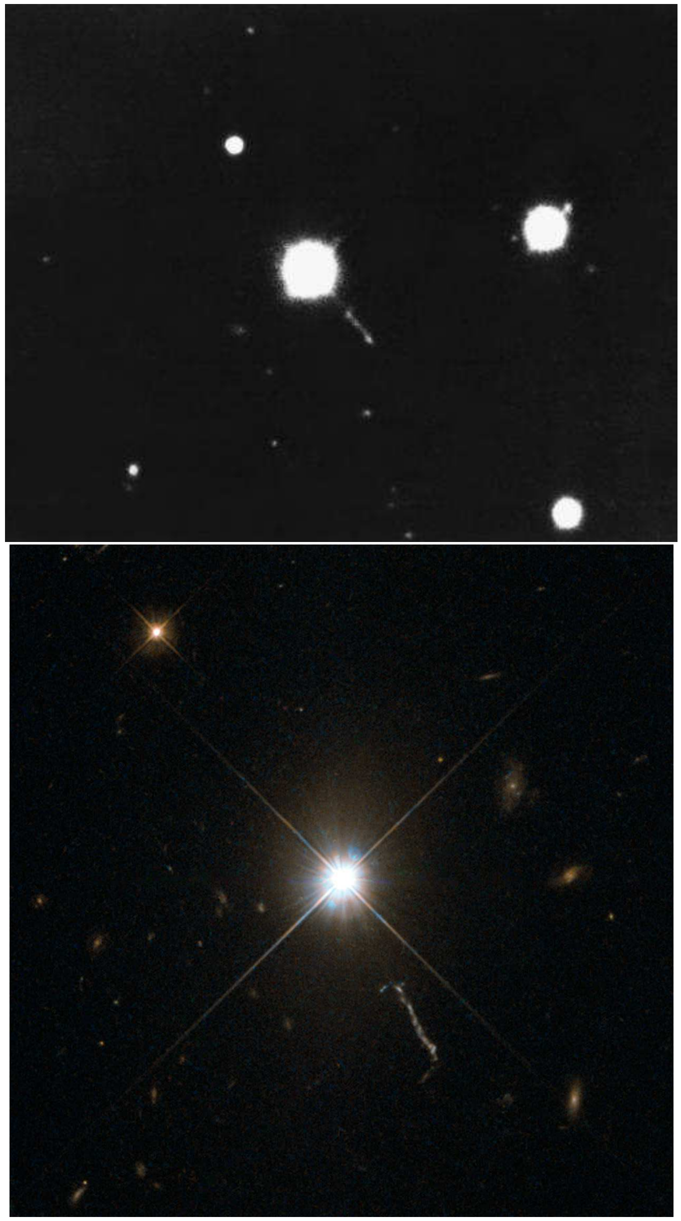

Figure 2: Top: Mayall 4m telecope image of 3C 273. North is up, east to the left. Bottom: HST-image of 3C 273. Note the change in resolution between the two images.

6. 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.

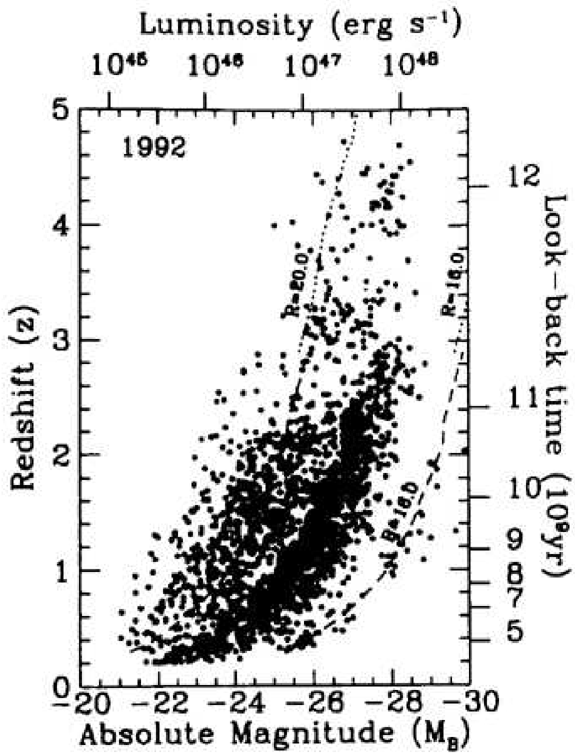

Figure 3: Absolute magnitude and luminosity of optically selected Quasars.

7. Determine the maximal dimension of the emission region responsible for the largest variations in the 3C 273 light curve in Figure 4. Use the shortest time between the minimum and maxiumum in the lightcurve as a proxy for the linear dimension (the time the light needs to travel for a certain distance). How does the linear dimension compare to the size of the solar system? The upper horizontal gives the time in Julian dates. The Julian dates (abbreviated JD) are simply a continuous count of days and fractions since noon Universal Time on January 1, 4713 BC (on the Julian calendar).

8. 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? Why do we show λF_λ (or νF_ν here) vs $\log(\lambda)$ instead of F_λ vs $\log(\lambda)$?

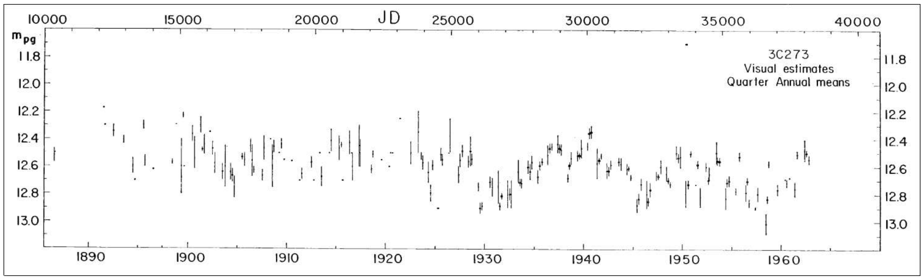

Figure 4: Light curve of 3C 273.

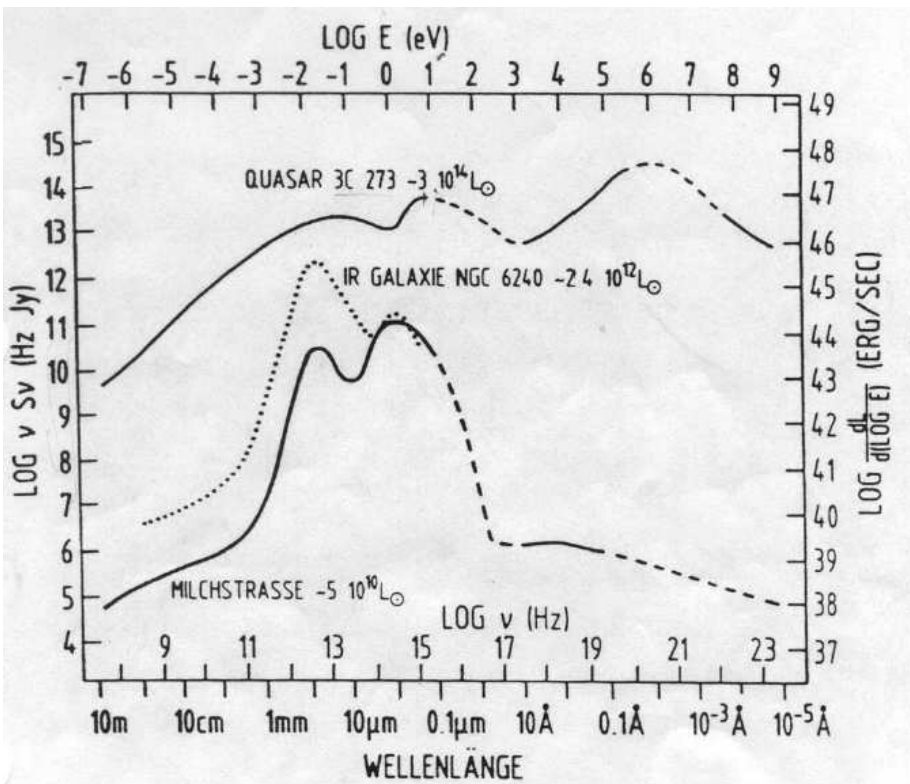

Figure 5: Spectral energy distribution of 3C 273, the Milky Way, and an IR–galaxy.

9. What is VLBI? VLBI maps of 3C 273 in Figure 7 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?

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

$$v_\perp = \dot{\Theta} \frac{d(z)}{1+z} \quad . \tag{2}$$

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 6).

$$v_\perp = c \frac{\beta_k \ \sin}{1 - \beta_k \cos\ i} \quad . \tag{3}$$

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

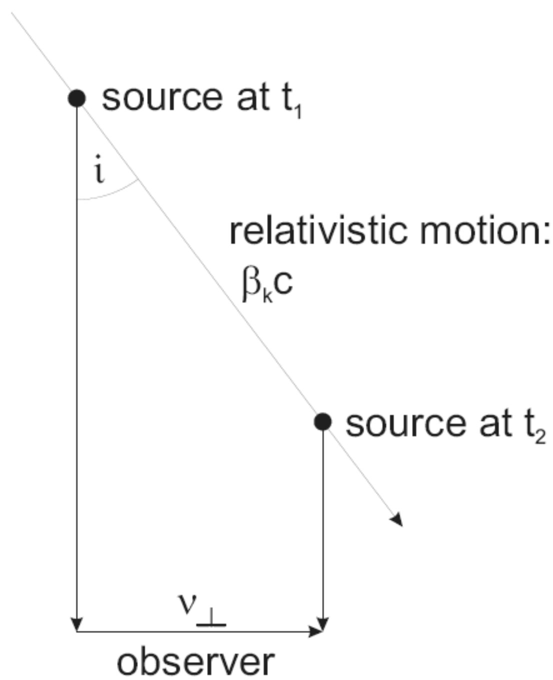

Figure 6: Superluminal motion.

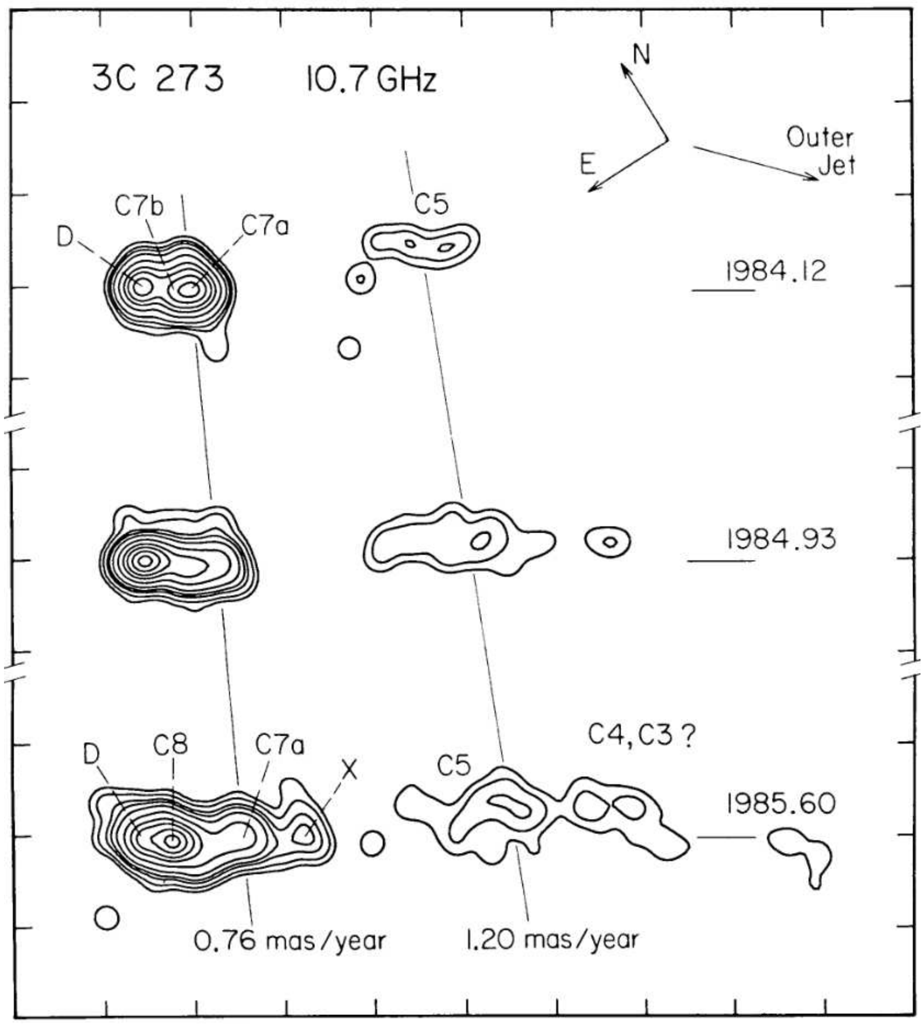

Figure 7: Superluminal motion in the jet components of 3C 273. The diagonal lines represent fits to the proper motions of the centroids of knots C5 and C7a of the jet relative to the core (Cohen, M.H. et al. 1987, ApJ, 315, L89).