

Chapter 2

Pointing the Telescope: Astronomical Coordinates and Sky Catalogs

The coordinates of the objects in the sky are of paramount importance for observational astronomers. The position of known targets is necessary to plan the observations. The identification of a new source is always accompanied by the determination of the position with high precision and the comparison with catalogs of known objects. In the following, the coordinates and the measure of time in astronomy will be discussed with the practical purpose of planning an observation. A detailed technical discussion of astronomical coordinates can be found in [1, 2]. The evolution of Internet has made the planning of observations easier. The coordinates of an astronomical object can be accessed on line, building the charts of the sky region around the target and accessing the related literature. The sky surveys have produced a large number of catalogs of sources at all wavelengths.

2.1 Astronomical Coordinate Systems

The celestial objects appear to be on the *celestial sphere*, an arbitrarily large sphere enclosing the Earth. A system of *celestial* coordinates uses two spherical coordinates, similar to the terrestrial latitude and longitude [1–3]. A celestial coordinate system is defined by a fundamental circle and a fixed point on it. The terrestrial equator and the meridians are examples of *great circles*, circles on the sphere defined by a plane crossing the center of sphere; on the other hand, the parallels are examples of *small circles*, since their planes do not cross the Earth center. Some basic definitions will be used in the following:

- **Celestial Poles:** the North and South Celestial Poles are defined by the Earth axis, as the projections of the terrestrial poles on the celestial sphere; the elevation of the North Celestial Pole above the horizon is equal to the latitude of the observatory.
- **Celestial Equator:** the projection of the Earth equator on the celestial sphere.

- Zenith, Nadir: the points above and below the observer.
- Meridian: the great circle that intercepts the poles, the zenith, and the nadir.

The celestial objects show an apparent motion in the sky, rising, achieving a maximum altitude above the horizon, and setting. The objects can be observable during some part of the year or could be not observable at all, at the position of the observer. Only circumpolar objects can be observed over the whole year.

The most intuitive coordinate system is the *alt-azimuth system*, based on the location of the observer. The reference plane is the local horizon; the North is the origin of the *azimuth* coordinate A that varies from 0 to 360° toward East, in analogy to the terrestrial longitude. The other coordinate, similar to the latitude, is the elevation h above the horizon, the *altitude*, that varies from 0 to 90°. The zenith distance introduced in the previous chapter is the complement to 90° of the altitude. The alt-azimuth system depends on the position of the observer and on the epoch of observation. The altitude of the star at the meridian is the maximum altitude above the horizon, the culmination. Part of the sky around the celestial pole will always be accessible to observers of one hemisphere.

The *equatorial system* is the most important coordinate system for astronomy. The equatorial coordinates of most objects are slowly varying; thus, they can be considered as fixed stars. The equatorial system is an approximation to an inertial reference system, since it is almost fixed in space. The equivalent of the longitude and latitude are the *right ascension* and the *declination*, defined by the Greek symbols α and δ . The declination measures the altitude above the celestial equator, increasing in the northern direction and decreasing in the southern direction. Right ascension starts from a reference point, the *First Point of Aries*, the point where the Sun crosses the celestial equator at the spring equinox. It is the equivalent of Greenwich longitude on Earth, increasing in the eastern direction. Right ascension and declination can be measured in angular units. The declination increases from 0 to 90° in the northern direction and decreases from 0 to -90° in the southern direction. Historically, the right ascension is measured in time units, dividing the great circle, 360°, into 24 hours. The right ascension increases from 0 to 24 h moving from the first point of Aries in the eastern direction. The meridian of the observer intercepts a different right ascension value in time. The hour angle HA is zero when the object is at meridian and changes from negative to positive values when it moves from East to West during the diurnal motion.

The equations of transformation between the two coordinate systems depend on the latitude φ of the observatory. The altitude h and the azimuth A of an astronomical source as a function of its right ascension and declination and of the hour angle are given by [3]:

$$\sin h = \sin \delta \sin \varphi + \cos \delta \cos \varphi \cos HA \quad (2.1)$$

$$\tan A = \frac{\sin HA}{\sin \varphi \cos HA - \cos \varphi \tan \delta} \quad (2.2)$$

The Sun appears to move along the *Ecliptic*. The Earth rotation axis is tilted by an angle of 23.4° , the obliquity of the ecliptic, with respect to the normal to the ecliptic plane. The Earth axis is slowly precessing, due to the gravitational torque of the Sun, the Moon and the planets, causing a small change in time of the equatorial coordinates. It is mandatory to state the epoch at which the astronomical coordinates are referred. The details will be discussed in the section about the definition of time in astronomy.

The *Ecliptic System* uses the ecliptic as the fundamental plane, and the first point of Aries, the intersection of the celestial equator with the Ecliptic plane, as the reference direction. The coordinates are the *ecliptic latitude* and the *ecliptic longitude*. The ecliptic latitude is the latitude above the ecliptic plane, while the ecliptic longitude is measured from the first point of Aries moving toward the East. The ecliptic system is useful for describing the motion of objects belonging to the solar system.

The *Galactic System* is different from the previous systems, since it is based on arbitrary definitions of the reference plane, the plane of the Milky Way, and of the reference direction, toward a conventionally defined galactic center. The two coordinates are the *Galactic Latitude* b and *Galactic Longitude* l . The galactic longitude increases from 0 to 360° moving toward East and starting from a reference direction pointing towards the galactic center. The Galactic Center and the Galactic North Pole are defined by the following coordinates:

- Galactic center: $\alpha = 17 \text{ h } 42 \text{ m } 34 \text{ s}$, $\delta = -28^\circ 55'$
- Galactic North Pole: $\alpha = 12 \text{ h } 49 \text{ m}$, $\delta = +27^\circ 24'$

The coordinates are defined at the epoch J1950 that will be discussed below.

2.2 The Measure of Time

Astronomy has provided the first methods to measure time, using the diurnal motion of the Sun. The declination of the Sun varies in the interval between $+23^\circ 26'$ and $-23^\circ 26'$. The highest and lowest declination values correspond to the *summer solstice* and *winter solstice*, occurring approximately on June 21 and December 21. The crossings of the celestial equator correspond to the *vernal equinox* (from South to North) and to the *autumn equinox* (from North to South) that occur on March 21 and September 23; at the equinox, day and night have equal lengths. The right ascension of the Sun increases at a rate of 4 min per day. At the vernal equinox, the right ascension of the Sun is 0h, while at the autumn equinox is 12h. At the summer solstice and winter solstice, the right ascension of the Sun is 6 and 18 h, respectively.

During the revolution of the Earth around the Sun, it appears to move along the ecliptic from West to East at less than one degree per day, since the Earth completes 360° in 365 days. The reference for daily timekeeping is set by the daily motion of the Sun. The *solar day* is defined as the time between two consecutive transits of the Sun at the meridian. The apparent solar time is the hour angle of the Sun. The real

Sun does not move with constant speed, because of the inclination of the ecliptic and of the ellipticity of the Earth orbit. The difference between the real and the mean Sun is described by the *Equation of Time*. The *Mean Solar Time* is the apparent time corrected for the effects mentioned above. The *Equation of Time* describes the difference between the real solar time and the mean solar time. The civil time, split into 24 h, is based on the mean solar day that assumes that the Sun is moving with constant speed across the sky.

The astronomical timekeeping [1, 2] is based in the *Universal time* (UT), the local time at Greenwich, with a time span of 24 h. The *civil time* is the mean solar time with the addition of twelve hours. The *Universal time* is the civil time at the Greenwich meridian. Local time is computed starting from Greenwich time according to the time zone of the observer.

Several definitions of the second have been adopted in time [1]. The original UT second has been originally defined as $\frac{1}{86400}$ of the mean solar day. A different definition of the second as the $\frac{1}{31556925.9747}$ of the tropical year 1900 lead to the Ephemeris Time (ET). The *Atomic Time* was defined in 1967 independently from astronomical phenomena as the time interval corresponding to 9 192 631 770 transition of ^{137}Cs . The *International Atomic Time* (TAI) was defined in 1971 as the weighted mean of different atomic clocks. The astronomical and atomic timescales were unified by the *Coordinated Universal Time* (UTC) that varies at the same pace as the TAI time, but is slightly dephased. Leap seconds are added each one or two years to synchronize the two systems. The *Terrestrial Time* (TT) is defined as the TAI time with the addition of 32.182 s. Two additional timescales are in use, referred to the geocentric barycenter and the solar system barycenter, the *Geocentric Coordinates Time* (TCG) and the *Barycentric Coordinated Time* (TCB).

When it is necessary to know the interval between two events, the Universal time is replaced by another system, the *Julian Date* (JD) system. In the Julian system, the date is computed using an origin at the First of January 4713 BC: all relevant dates for astronomy are described by positive numbers. As a convention, days are starting at noon. For reference, the Julian Day 2450000 occurred on October 9, 1995, at 12 h. To avoid long numbers, the Julian Date system is sometimes replaced by the *Modified Julian Date* (MJD) system, where: $MJD = JD - 2400000.5$.

The *epoch* is an instant in time. The astronomical standard definition of dates uses the order: year, month, day, hours, minutes, seconds, as in 2015 December 07, 00 h 39 m 00 s. The astronomical coordinates of an object, right ascension and declination, are always referred at an epoch. Several epochs have been historically used for reference:

- B1900.0, Besselian epoch J1900.000857
- B1950.0, Besselian epoch J1949.999789
- B2000, Besselian epoch J1999.998722
- B1950.000210, Besselian epoch corresponding to Julian epoch J1950.0, reference is 1950 January 1, 00 h 00 m 00 s
- B2000.001278, Julian epoch J2000, reference is 2000 January 1, 00 h 00 m 00 s

The actual reference epoch is J2000 that has superseded J1950.0.

The *Sidereal Time* (ST) is defined as the right ascension (RA) of the observer meridian and shares the units of time with the right ascension and the hour angle (HA) defined above. The three quantities are linked by the relation:

$$ST = RA + HA \quad (2.3)$$

Due to the Earth revolution, in one year, the stars will make about 366 diurnal cycles, while the Sun will make only about 365 cycles. The sidereal time runs faster than the solar time. The length of the sidereal day is 23 h, 56 min, 4 s. Thus, the sidereal time advances two hours per month. The zero of the sidereal time can be understood recalling that the first point of Aries, the zero of the right ascension, corresponds to the vernal equinox. On that day, the sidereal time at noon is 0 h, while the solar time is 12 h. At the autumn equinox, the sidereal and the solar time at noon will be 12 h and 0 h, respectively. Since astronomical observations are performed during the night, it is necessary to deal with the sidereal time at midnight that will be 12 h at vernal equinox and 0 h at the autumn equinox. The Greenwich and local sidereal time can be obtained online using the data service at the United States Naval Observatory.¹

2.3 Astrometry

Astrometry is a sector of astronomy dealing with the measurement of the positions of celestial sources, including the variations in time. Astrometric observations have been performed with ground-based instruments until the advent of the Hubble Space Telescope (Chap. 4). The equatorial coordinates are measured at ground-based observatories by *transit telescopes*, also called *meridian circles*. The instrument observes only the celestial objects at the meridian and is equipped with a graduated circle positioned in the circle of the meridian and a fixed reference pointing to the zenith that is used to determine the elevation angle of the pointing direction. The observations can lead to *large angle astrometry*, for the determination of the absolute positions of celestial objects, or to *small angle astrometry*, where the positions are measured relative to reference objects in the frame. The effect of the refraction and of the atmospheric turbulence (Chap. 4) limit the accuracy to some tens milli arc seconds. Optical astrometry in space is not affected by atmospheric effects. The Hipparcos mission has achieved a positional accuracy better than 1 milli arc second for the 120000 observed objects with magnitudes up to 12. The GAIA mission will perform a sky survey down to magnitude 20, with an accuracy better than 10 micro arc seconds for bright objects and better than 1 milli arc second for fainter objects.

The present reference system is the *International Celestial Reference System* (ICRS), proposed by the International Astronomical Union in 1991. The fundamental plane of the systems is the equatorial plane of the Earth, while the reference point is

¹aa.usno.navy.mil/data/docs/siderealtime.php.

the vernal equinox; both of them are defined at epoch J2000.0. The ICRS is defined using extra galactic objects, the quasars, that can be considered fixed within some micro arc seconds per year. The technique of *Very Long Baseline Interferometry* (VLBI) in the radio domain (Chap. 12) allows to estimate the positions of objects with an accuracy better than 1 milli arc second. The system is a good approximation to an inertial system.

2.4 Nomenclature and Catalogs

The identification of an astronomical source and its classification rely on the historical definition of the name of stars and constellations. The telescope surveys over the whole electromagnetic spectrum are continuing adding new objects. To date, Internet resources and digital data have replaced the traditional paper and photographic storage of the first astronomical surveys. The *Centre de Données astronomiques de Strasbourg* (CDS²) is the repository dedicated to the storage, upgrading, and distribution of the information about astronomical objects. The CDS is the source of different databases:

- *Simbad*³: astronomical database for the identification of astronomical objects; it can be queried either by the name of the object or by the astronomical coordinates. The archive contains the main data of the sources, their identification in different surveys, and the bibliographic references.
- *VizieR*⁴: access to more than 15000 catalogs and more than 14000 data tables (May 2016) that can be queried and cross correlated. The VizieR photometry tool⁵ visualizes photometric points extracted from all catalogs in VizieR to build the spectral energy distribution (SED).
- *Aladin*⁶: interactive sky atlas to access, visualize, and analyze online digitized astronomical images produced by surveys, with the possibility to superimpose data from different surveys and catalogs. Aladin is the tool used to produce the *finding charts*, the maps of the region of the sky used for observation (Chap. 13).

The Simbad utility provides access to the bibliographic references, to several measured physical quantities, and to the Aladin sky atlas. The result of the Simbad query for the quasar 3C 273 and the corresponding finding chart built with Aladin are shown in Figs. 2.1 and 2.2.

The example of Fig. 2.1 shows the rich nomenclature of astronomical names: The object has several names, since it has been observed in different surveys. The brightest stars of the constellations were classified by Bayer in 1603. They were identified with

²<http://cds.u-strasbg.fr/>.

³<http://simbad.u-strasbg.fr/simbad/>.

⁴<http://vizier.u-strasbg.fr/index.gml>.

⁵<http://vizier.u-strasbg.fr/vizier/sed/>.

⁶<http://aladin.u-strasbg.fr/aladin.gml>.

3c 273

<http://simbad.u-strasbg.fr/simbad/sim-id?Ident=3...>

[illegible]

Fig. 2.1 Simbad query for the quasar 3C 273

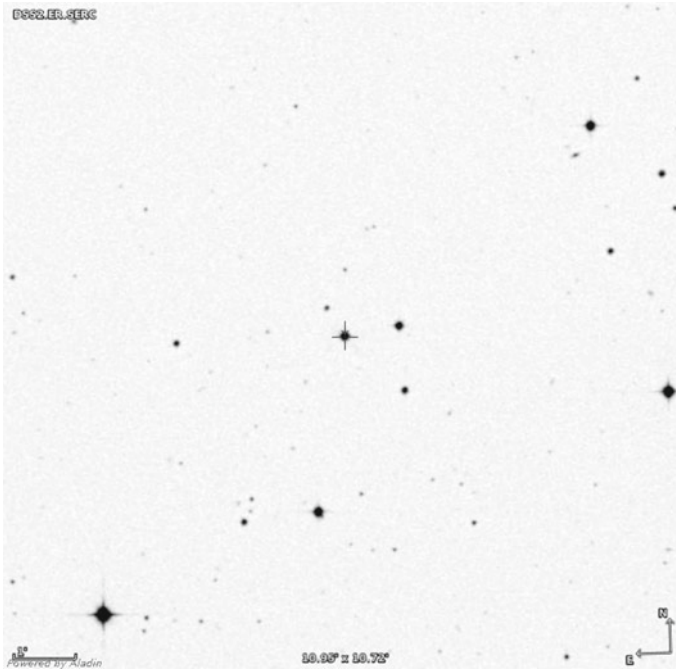


Fig. 2.2 Aladin finding chart for the quasar 3C 273

Greek letters and the name of the constellation as in α Orionis (Betelgeuse), with brightness decreasing with the order of letters of the Greek alphabet. The catalog by Flamsteed (1725) identified the stars by a number followed by the constellation name, as 19 Orionis for Rigel. The variable stars are named using Latin letters or combination of them. The first variable stars in a constellation are named from R to Z, as in R CrB. The following name series combine two letters of the alphabet, from RR to RZ, then from SS to SZ, and so on, ending with ZZ; two examples are RR Lyr and SS Cyg. The two letter system then moves to the beginning of alphabet, with AA to AZ, and so on, ending with QZ. The letter system produces 334 different names; additional systems are labeled with the letter V followed by a number starting from 335; two examples are V5558 Sgr and V404 Cyg. The world of astronomical transients has added new definitions. The gamma-ray bursts (GRB) are named with the Letters GRB followed by the date written as yymmdd; in case there is more than one GRB per day, those after the first one get an additional letter. Supernovae are named using the letters SN followed by the year written as yyyy and by a capital letter, from A to Z and, if needed, starting again from aa. The recent discovery of gravitational waves announced in 2016 has added a new definition for a new astronomy, GW for gravitational waves, followed by the date of the event in the format yymmdd. The first reported event is GW150914.

The first star catalog, realized by Bessel during the nineteenth century, included a few tens of stars. During the twentieth century, it was replaced by the *Fundamental Katalog* (versions FK4 and FK5) with about 1500 stars. More recent catalogs have introduced new classifications, which is made of a set of letters and a progressive number. Some of them will be briefly summarized here. The symbols BD, CD label the *Bonner Durchmusterung* and *Cordoba Durchmusterung*, two photographic surveys of the two hemispheres up to magnitude 10. The label HD labels the *Henry Draper Catalog*, originated by a donation to the Harvard Observatory, that includes more than three hundreds thousands stars up to magnitude 9. The Schmidt telescope at Palomar has been used for the *Palomar Observatory Sky Survey* (POSS) of 1957, a photographic survey including stars from the North Celestial Pole down to declination -33° and up to magnitude 20; the survey was completed by the Australian survey that extended the declination range to -90° . The label USNO refers to the catalog of the *United States Naval Observatory* that has digitized the POSS and other surveys and includes about one billion stars up to magnitude 21. Additional catalogs are built by ground-based and space-based observatories, by adding new prefixes to the nomenclature.

2.5 Internet Resources

The amount of Internet resources for astronomers is steadily evolving, and any attempt to build an exhaustive compilation would become out of date very soon. The present section is a road map addressing the general topics of data collection and storage and the development of management tools that have lead to the birth of the Virtual Observatory. The data sets produced by a large number of sky surveys and space missions are available online and contain the potential for new discoveries. The Simbad, Aladin, and VizieR facilities discussed above are high-level data products that are interfaced to a rich world of archives. Another high-level product is the NASA/IPAC Extragalactic Database (NED)⁷ that combines the imaging and spectral data of millions of objects external to the Milky Way.

Some widely used astronomical archives are:

- Palomar Observatory Sky Surveys (POSS I and POSS II): the photographic plates which have been digitized and are available at The STScI Digitized Sky Survey site⁸
- Sloan Digital Sky Surveys (SDSS-I,⁹ SDSS-II,¹⁰ SDSS-III¹¹): a series of massive spectroscopic surveys providing images and spectra for millions of sources.

⁷<https://ned.ipac.caltech.edu/>.

⁸http://stdatu.stsci.edu/cgi-bin/dss_form.

⁹<http://www.sdss.org/>.

¹⁰<http://www.sdss2.org/>.

¹¹<http://sdss3.org/>.

- NASA/IPAC Science Archive¹²: archive collecting the data of the infrared surveys and missions (2MASS, WISE, Herschel, Planck, IRAS).
- Mikulski Archive for Space Telescopes (MAST)¹³: access to the astronomical data archives of optical, ultraviolet, and near-infrared observatories, including the Hubble Space Telescope (HST) and the Digitized Sky Survey (DSS).
- High Energy Astrophysics Science Archive Research Center (HEASARC)¹⁴: repository of X-ray and gamma ray missions (RXTE, Swift, Rosat, Chandra, XMM-Newton, Fermi, INTEGRAL, etc.).

The data of archives generally are proprietary for a time interval of one or two years, before becoming available to the whole community. The *Virtual Observatory* (VO)¹⁵ is the environment managing the electronic access to the archives of ground- and space-based observatories. The effort has lead to the development of different software tools addressed to query the world archives that can run as stand-alone programs or as Web-based utilities:

- VOPlot¹⁶: tool for the analysis and the graphing of data.
- Tool for OPerations on Catalogues And Tables (TOPCAT)¹⁷: an interactive graphical environment to plot and analyze data
- SPLAT-VO¹⁸: tool for display and analysis of astronomical spectra.
- Specview¹⁹: for display and loading of spectra and comparison with libraries of spectra.
- VOSpec²⁰: spectral analysis tool with libraries of atomic and molecular data.

The astronomical literature can be directly accessed at the SAO/NASA Astrophysics Data System (ADS)²¹, a portal supporting three bibliographic databases. For each paper, ADS links to the publisher site for the full text or to a scanned versions; the systems also tracks the citations to the papers. The electronic archive *arXiv*²² has replaced the old paper preprints and provides the prepublication version, freely downloadable, of most astronomical papers of the last two decades.

¹²<http://irsa.ipac.caltech.edu/frontpage/>.

¹³<https://archive.stsci.edu/>.

¹⁴<http://heasarc.gsfc.nasa.gov/>.

¹⁵<http://www.ivoa.net>, <http://www.euro-vo.org/>.

¹⁶<http://vo.iucaa.ernet.in/~voi/voplot.htm>.

¹⁷<http://www.star.bris.ac.uk/~mbt/topcat/>.

¹⁸<http://www.g-vo.org/pmwiki/About/SPLAT>.

¹⁹http://www.stsci.edu/institute/software_hardware/specview/.

²⁰<http://www.cosmos.esa.int/web/esdc/vospec>.

²¹<http://www.adsabs.harvard.edu/>.

²²<http://arxiv.org>.

Problems

2.1 Using Simbad, Vizier, and Aladin find the astronomical coordinates and build the finding charts for the following objects, discussing the type of source and the main properties:

- HD 209458
- Barnard's star
- SS Cyg
- M67
- OJ 287
- Crab

References

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2. Smarr, W. H. M.: *Textbook on Spherical Astronomy*. Cambridge University Press (1977)
3. Bely, P.: *The Design and Construction of Large Optical Telescopes*. Springer, New York (2013)

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