Observation of planetary motion using a digital camera

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Historical background

Astronomical observation and modelling played an important role in the history of science [1-3]. Tycho Brahe (1546-1601) was able to determine position of planets and stars with up to one arc minute accuracy. These data could not be explained by any of the models discussed at that time. Johannes Kepler (1571-1630) invented his famous laws in order to explain the data of Tycho. Galileo Galilei (1564-1642) was the first one to use a telescope for astronomical observation, and he discovered the satellites of Jupiter. Consequently, Isaak Newton (1643-1727) found the law of gravitation as the underlying principle of planetary motion:

$$F = -G\frac{mM}{r^2}$$

It is important to state that Newton found this law, including a complete theory of mechanics, without knowing either the distance *r* or the gravitation constant *G*. Edmund Halley (1656-1742), who cooperated with Newton on the planetary motion problem, made proposal of measuring the earth‘s distance from the sun, from which all other distances in the solar system could be derived through the third Kepler law. This project was realized long after the death of Newton and Halley, by Captain Cook in 1756. Even later in 1798, Cavendish measured the gravitation constant *G*.

Today, we have different ways to teach the law of gravitation. One could write down the formula and mention Newton’s genius. But this leaves an open question: Where do the numbers come from? In high school, we are able to duplicate the historic steps and repeat central experiments, i.e. using a Cavendish gravitation balance, and analyze published data of the Venus transit of June 8th, 2004. With *r* and *G* measured, the mass of the sun can be determined: a major goal is achieved. In the context of historical view, it is very valuable to give student an impression on how fast planets move.

Observing planets

Planets can be observed with a broad variety of instruments ranging from the naked eye over telescopes to interplanetary space crafts. For educational purpose, the most powerful method is not necessarily the best one, because students might not understand the technical details and misinterpret the images.

Our Goal

The observation of planetary motion by naked eye is the natural approach. However, even in the simplest case of Venus one needs a period of at least one week to observe any motion at all, and other planets move even slower. This obstacle can be overcome with a SLR digital camera, when the motion of any of the large planets can be detected on two consecutive days. By most students, standard photographic camera should be considered everyday equipment rather than a specialized instrumentation. It is only a minor technical help.

Advantages of SLR camera

The field of view of an SLR digital camera is large, and yet the angular resolution is in the range of 0.5 arc minutes. The CCD sensor is very sensitive and high quality optics are available. It is has a wide range of other applications, e.g. IR and UV photography [4], and therefore a digital SLR is a useful acquisition for a high school in general.

The camera used her – a Nikon D70 – has a maximum sensitivity of 1600 ASA. With the 50mm/1.4 Nikkor lens, the sensor covers 32° in diagonal and the effective pixel width is 0.156mrad. Stellar constellation can be covered as a whole.

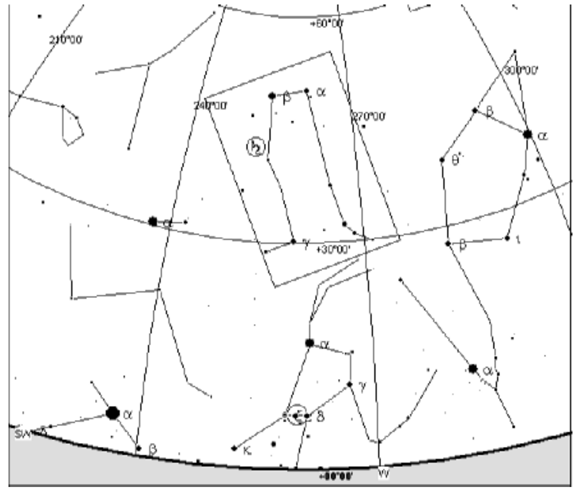

Figure 1: Field of view of the camera.

Saturn

Among the planets visible without technical aid, Saturn is the slowest and the most distant. Therefore it is a critical object to test the method. The motion over the sky background is dominated by the movement of the earth rather the motion of Saturn relative to sun.

Between two consecutive days (April 29th and April 30th 2005) the motion of Saturn is clearly resolved. The image coincides well with theoretical calculation using Cartes du Ciel [5]. The distance travelled within 24 hours is 4’. Tycho Brahe was able to measure such small angles without any optical instrumentation [1,2].

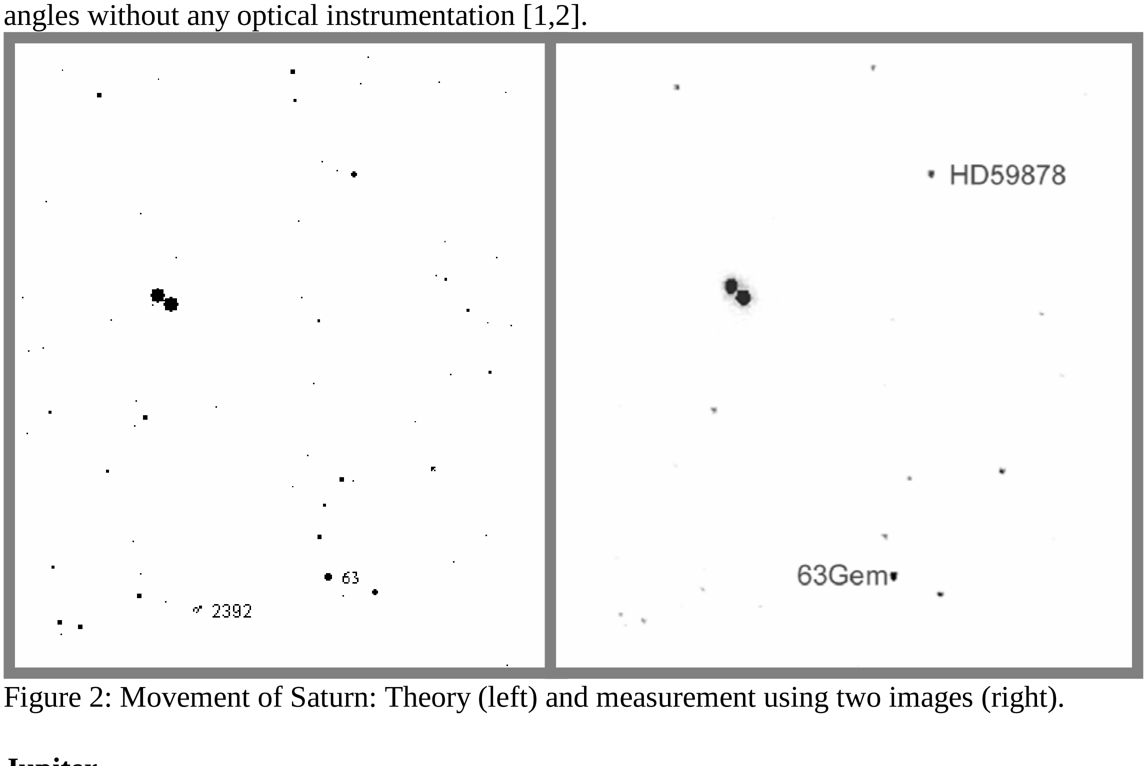

Figure 2: Movement of Saturn: Theory (left) and measurement using two images (right).

Jupiter

The satellites Io, Europa, Ganymede, and Callisto are not visible to the naked eye, though their brightness (5^m to 6^m) is sufficient in principle. This is causes by saturation of the eye due to Jupiter, being almost 2000 times brighter. With the camera, the satellites are clearly visible. The angle of view is large enough to get a realistic impression how far the satellites separated (compare to trees in the foreground). The full frame picture shows Jupiter in the upper part of Virgo, near γ Vir, on 4-27-2005. Red lines indicate the shape of the stellar constellation. The halo around Jupiter is cause by haze. Such poor observation condition does not affect the method. The central part is enlarged on the right.

Figure 3: full frame image of Jupiter (left) and enlargement of the Galilean satellites (right).

Working with students

Any serious course on the history of the gravitation law will require the observation of planetary motion at some point. The present method is fast and reliable, and works for any of the large planets Mercury, Venus, Mars, Jupiter and Saturn, i.e. it requires no special schedule.

Digital SLR cameras are constructed to be used by anybody. Though the special subject night sky requires some knowledge on manual settings of exposure and focus, the use of a camera is still much easier than the use of a telescope. The images can be inverted with standard software and printed out on plain paper a few minutes after exposure. Each student in a class can work with her own stellar map. One can make photographs on different days and let the students determine the angular speed of a certain planet by triangulation on the paper print.

In order to observe critical objects such as satellites of Jupiter and Saturn, one has to do enlargements which reveal the pixel structure. This can lead to a discussion of the trade between large field of view and angular resolution, especially if different lenses are used. Professional astronomers have the same problem. High sensitivity and easy data transfer is important for space based telescopes and interplanetary space crafts. In principle, the digital camera works the same way and has the same kind of limitations.

Though Uranus was not visible during the period of this project, the present results show that the demonstration of Uranus' motion will be easy. Due to the larger distance, one would have to wait several days. With a self made stellar map, students can locate its position in the night sky, though it is usually not visible to the naked eye under average observation conditions,

Another approach to use an everyday high-tech sensor in physics education is the Foucault pendulum tracked with a graphic tablet [6]. Same arguments apply in this case: The students cannot see the effect immediately, but they know how the sensor works and they have a good sense of the magnitude.

Technical Aspects

The *f* number, i.e. the factor by which the lens diameter is smaller than the focal length, must be as small as possible. While point-and-shot cameras have lenses in the f/4 to f/8 range, "faster" lenses are available for SLR cameras. Among these, the standard lens 50mm/1.4 is a perfect choice for our purpose. Depending on the manufacture, 35mm/2 or 28mm/2 could be interesting alternatives with even larger field of view.

Stopping down the lens reduces the amount of light collected through exposure, but it also reduces aberration of the lens and therefore increases resolution. Empirically, f/2.0 was found the optimum. Similar values are expected for other lenses with similar construction. A very critical object is Saturn with Titan.

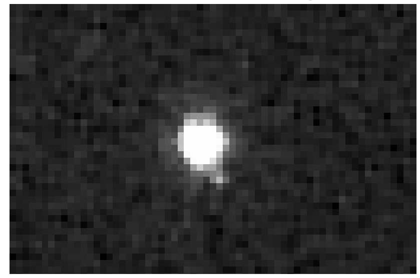

Figure 4: Saturn and Titan (8.4^m) at a distance of 2'42". The enlargement is 0.5° wide.

Rotation of the earth limits the useful exposure time to a few seconds. For longer exposure times, the stars' images are distorted. A star moves across the given sensor at a speed o one pixel in 2.13 seconds. Empirically, four seconds was found the best exposure time for many cases.

The auto focus system of the camera does not work with the night sky. Therefore, the lens has to be focused manually. Setting an auto focus lens to infinity does not yield sharp images. The correct infinity point has to be determined under daylight conditions and then reproduced at night (figure 5).

When working close to the noise level, any data reduction such used in JPEG causes problems. Therefore, the camera RAW format is used and the images are processed as TIFF files either with the freeware Nikon View or with Photoshop Elements 3.0

The resolution of the camera is highly anisotropic. For very critical work, one should choose the most critical structure parallel to the base of the camera, for example, parallel to the ecliptic when taking photos of Jupiter and its satellites.

References

[1] Carl Sagan and Ann Druyan, *Comet*, New York 1985 (german translation: *Der Komet*, 1985)

[2] Stephen Webb, *Measuring the Universe: The cosmological distance ladder*, Chichester 1999.

[3] F. Hund, *Geschichte der physikalischen Begriffe*, Mannheim 1973. (in german)

[4] Gorazd Planinšič, University of Ljubljana, Faculty of Mathematics and Physics, private communication at the conference (2005).

[5] Patrick Chevallier, *Cartes du Ciel* Version 2.76, available at www.astrosurf.com/astropc, 4/1/2005.

[6] Manfred Euler and Gert Braune, *Das grafische Foucault-Pendel*, Mathematisch-Naturwissenschatlicher Unterricht (MNU) 56/4, 206-211 (2003). (in german)

[7] Dennis di Cicco: *Simple Sky Photography with a Film Camera*, Sky and Telescope online archive, available at http://skyandtelescope.com/printable/howto/imaging/articel_162.asp, 5/30/2005.

[8] A. Weigert and H. J. Wendker, Astronomie und Astrophysik, Weinheim 1983. (in german)