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A Taste of Real Astronomy — The ESA/ESO Astronomy Exercises

Today, most big science projects are impossible to take on by a single research group or university. The expense makes collaborations and partnerships a must. The Hubble Space Telescope is jointly run as a partnership between the European Space Agency and NASA. The worlds largest optical-infrared telescope, the Very Large Telescope or VLT is located in Chile and operated by an intergovernmental research organisation called ESO, the European Southern Observatory. For more information on the European contribution to the Hubble Space Telescope go to: http://hubble.esa.int and for more on the VLT go to: http://www.eso.org.

This issue of "The Universe in the Classroom" is contributed by astronomers from the Education and Public Relations office of the European Southern Observatory. If you'd like more information about their education projects, they can be contacted at: info@astroex.org or go to their web site www.astroex.org. For more information on educational products from the American side, go to the Hubble Deep Field Academy at: http://amazing-space.stsci.edu/hdf-top-level.html

A Taste of Real Astronomy — The ESA/ESO Astronomy Exercises

by Arntraud Bacher, Lars Lindberg Christensen

Astronomy at the Frontline of Education

Astronomy is an accessible and visual science, making it ideal for educational purposes. Over the last few years the NASA[1]/ESA[2] Hubble Space Telescope and the ESO[3] telescopes at the La Silla and Paranal Observatories in Chile have presented ever deeper and more spectacular views of the Universe. However, Hubble and the ESO telescopes have not just provided stunning new images, they are also invaluable tools for astronomers. The telescopes have excellent spatial/ angular resolution (image sharpness) and allow astronomers to peer further out into the Universe than ever before and answer long-standing unsolved questions.

The analysis of such observations, while often highly sophisticated in detail, is at times sufficiently simple in principle to give secondary-level students the opportunity to repeat it for themselves.

In the Footsteps of Scientists

The "ESA/ESO Astronomy Exercise Series" has just been published, on the web and in print. These exercises allow 16-19 year old students to gain exciting hands-on experience in astronomy, making realistic calculations with data obtained by some of the world's best telescopes, Hubble and ESO's Very Large Telescope (VLT). Carefully prepared by astronomers and media experts, these exercises enable the students to measure and calculate fundamental properties like the distances to and the ages of different kinds of astronomical objects.

The application of scientific methods requires only a basic knowledge of geometry and physics. Students use ideas and techniques described in recent frontline scientific papers and are able to derive results that compare well with those obtained from the much more sophisticated analyses done by the scientists.

The language for the ESA/ESO Astronomy Exercise Series is English. There are several reasons for this choice — it is the language used most often among scientists. Good knowledge and practical experience in the use of this language is a valuable asset for all students, particularly for somewhat technical texts like these. In modern education it has been recognised that it is important to cross barriers between different subjects and to link them by using inter-disciplinary activities that develop and strengthen several different types of skills. Thus, we recommend that the English text of these exercises may also serve as exercise in the practical use of English. We are doing our best to provide versions in some of the other ESA/ESO member state languages.

All the exercises are constructed with a background text followed by a series of questions, measurements and calculations. The exercises can be used either as texts in traditional classroom format or, as the exercises are quite self-explanatory, be given to smaller groups as a part of 'project work'. The exercises are intended to be independent of each other. However, we recommend that the relevant parts of the Toolkits are worked through with the students prior to assigning the exercises, unless the content is already familiar to them.

Focus on basic themes

The first four exercises focus on measurements of distances in the Universe, one of the most basic problems in modern astrophysics.

The students apply different methods to determine the distance of astronomical objects such as the supernova SN 1987A, the spiral galaxy Messier 100, the Cat's Eye Planetary Nebula and the globular cluster Messier 12. With these results it is possible to make quite accurate estimates of the age of the Universe and its expansion velocity. All thiswithout the use of computers or sophisticated software.

Students can also perform 'naked-eye photometry' by measuring the brightness of stars on two VLT images (taken through blue and green optical filters, respectively). They can then construct the basic luminosity-temperature relation (the "Hertzsprung-Russell Diagram") providing a superb way to gain insight into fundamental stellar physics.

Notes

1. National Aeronautics and Space Administration
2. European Space Agency
3. European Southern Observatory

A Taste of Real Astronomy — The ESA/ESO Astronomy Exercises

Six booklets

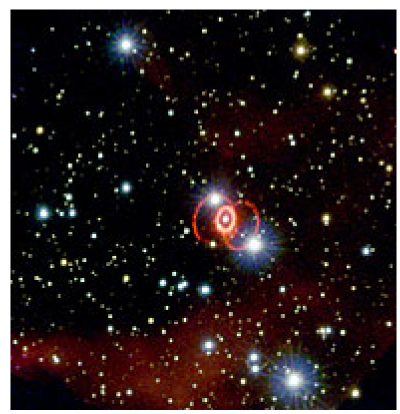
The exercises are now available on the web and in six booklets (100 pages in total), titled:

"General Introduction" (an overview of the exercise series),
"Toolkits" (explanation of basic astronomical and mathematical techniques),
"Exercise 1: Measuring the Distance to Supernova 1987A",
"Exercise 2: The Distance to Messier 100 as Determined by Cepheid Variable Stars",
"Exercise 3: Measuring the Distance to the Cat's Eye Nebula" and
"Exercise 4: Measuring a Globular Star Cluster's Distance and Age".

The booklets are sent free-of-charge to high-school teachers on request and may be downloaded as PDF files from the web site. More exercises will follow in the future.

Contact: info@astroex.org, www.astroex.org

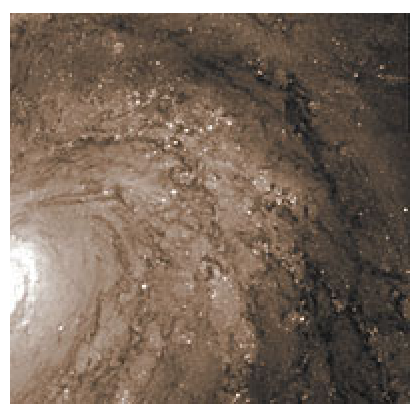
Exercise 1 - Measuring the Distance to Supernova 1987A



Quick Summary

The geometry of the nearest ring around Supernova 1987A (SN1987A) is introduced. We then define the scale of the Hubble image of the supernova so that the angular diameter of the ring and also the inclination of the ring relative to the plane of the sky can be found. Observations from Earth show how light from the supernova reached the different parts of the ring. Using light intensity measurements and the speed of light, the physical dimensions of the ring can be found. Once both the angular and the physical size of the ring have been determined, we can determine the distance to SN 1987A itself.

Exercise 2 - The Distance to Messier 100 as Determined By Cepheid Variable Stars



Quick Summary (click here for the complete exercise)

In this exercise we measure the period and apparent magnitudes of Cepheid variables in the galaxy M100. The absolute magnitude is derived using the Period-Luminosity relation and the distance to M100 can then be determined using the distance relation. Finally we calculate a value for the Hubble constant (using a value for the recession velocity of M100 observed by other scientists) and estimate the age of the Universe.

Exercise 3 - Measuring the Distance to the Cat's Eye Nebula

Quick Summary

We measure the angular expansion velocity of the Cat's Eye Nebula by careful investigation of two Hubble images taken in 1994 and 1997. With the help of tangential velocity measurements from an earlier scientific paper, it is possible to determine the distance to the nebula. We also derive the distance by looking at how much the radial intensity profiles of prominent features in the two images have changed between 1994 and 1997.

Exercise 4 - Measuring a Globular Star Cluster's Distance and Age

Quick Summary

We measure blue (mB) and green (visual, mV) magnitudes of selected stars in the outer regions of a globular cluster shown on VLT images, convert the (mB-mV) values into stellar surface temperatures (T) and plot the mV values as a function of the T values on a Hertzsprung-Russell diagram. The cluster's Main Sequence, seen in the plotted diagram, is compared with a distance-calibrated standard Main Sequence from the nearby Hyades cluster. The distance to the cluster can be determined by Main Sequence fitting and using the distance modulus. The cluster's age, which incidentally places a lower limit on the age of the Universe, can be estimated from the position of the turn-off point on the Main Sequence.

A Taste of Real Astronomy — The ESA/ESO Astronomy Exercises

The ESA/ESO Astronomy Exercise Series 2
The Distance to Messier 100 as Determined by Cepheid Variable Stars

Arntraud Bacher, Lars Lindberg Christensen

Quick Summary

In this exercise we measure the period and apparent magnitudes of Cepheid variables in the galaxy M100. The absolute magnitude is derived using the Period-Luminosity relation and the distance to M100 can then be determined using the distance relation. Finally we calculate a value for the Hubble constant (using a value for the recession velocity of M100 observed by other scientists) and estimate the age of the Universe.

Measuring distances with Cepheids

Measuring the *distance* to an astronomical object is a difficult task and is one of the greatest challenges facing astronomers. Over the years a number of different distance estimators have been found. One of these is a class of special stars known as Cepheid variables.

Cepheids are rare and very luminous stars that have a very regularly varying luminosity. They are named after the star d-Cephei in the constellation of Cepheus, which was the first known example of this particular type of variable star and is an easy naked eye object.

In 1912 the astronomer Henrietta Leavitt (see Fig. 1) observed 20 Cepheid variable stars in the Small Magellanic Cloud (SMC). The small variations in distance to the individual Cepheid variable stars in the Cloud are negligible compared with the much larger distance to the SMC. The brighter stars in this group are indeed intrinsically brighter and not just apparently brighter, because they are closer. Henrietta Leavitt uncovered a relation between the intrinsic brightness and the pulsation period of Cepheid variable stars and showed that intrinsically brighter Cepheids have longer periods. By observing the period of any Cepheid, one can deduce its intrinsic brightness and so, by observing its apparent brightness calculate its distance. In this way Cepheid variable stars can be used as one of the 'standard candles' in the Universe that act either as distance indicators themselves or can be used to calibrate (or set the zero point for) other distance indicators. Cepheid variables can be distinguished from other variable stars by their characteristic light curves (see Fig. 2).

Figure 1: Henrietta Leavitt

The understanding of the relative brightness and variability of stars was revolutionised by the work of Henrietta Swan Leavitt (1868-1921). Working at Harvard College Observatory, Leavitt calibrated the photographic magnitudes of 47 stars precisely to act as standard references or 'candles' for the magnitudes of all other stars. Leavitt discovered and catalogued over 1500 variable stars in the nearby Magellanic Clouds. From this catalogue, she discovered that brighter Cepheid variable stars take longer to vary, a fact used today to calibrate the distance scale of our Universe (Courtesy of AAVSO).

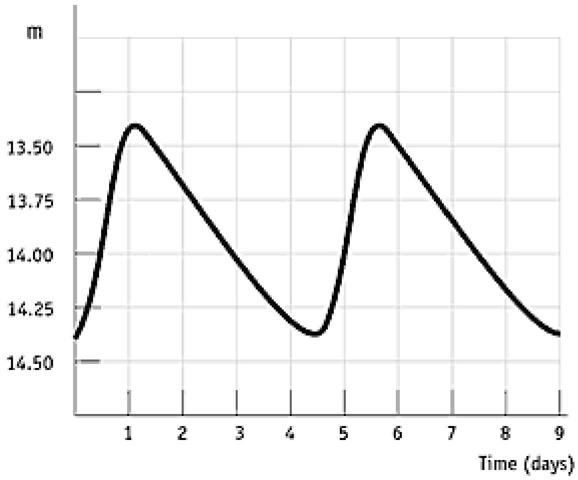


Figure 2: Typical Cepheid light curve

The light curve for a Cepheid variable star has a characteristic shape, with the brightness rising sharply, and then falling off much more gently. The amplitude of the variations is typically 1-2 magnitudes.

The most accurate measurements of both velocity and distance are naturally obtained for objects that are relatively close to the Milky Way. Before the NASA/ESA Hubble Space Telescope was available, ground-based observatories had detected Cepheid variables in galaxies with distances up to 3.5 Megaparsecs from our own Sun.

However, at this sort of distance, another velocity effect also comes into play. Galaxies attract each other gravitationally and this introduces a non-uniform component to the motion that affects our measurements of the uniform part of the velocity arising from the expansion of the Universe. This non-uniform part of the velocity is known as the peculiar velocity and its effect is comparable with the expansion velocity in our local part of the Universe. In order to study the overall expansion of the Universe, it is necessary to make reliable distance measurements of more distant galaxies where the expansion velocity is significantly higher than the peculiar velocity. Hubble has measured Cepheid variables in galaxies with distances of up to ~20 Megaparsecs.

Before Hubble made these measurements astronomers argued whether the Universe was 10 or 20 billion years old. Now the agreement is generally much better — the age of the Universe is believed to be somewhere between 12 and 14 billion years.

One of the Hubble's Key Projects had as a longterm goal a more accurate value for the Hubble constant and the age of the Universe. Eighteen galaxies located at different distances have been monitored to reveal any Cepheid variables. One of these galaxies is M100 (see Fig. 3).

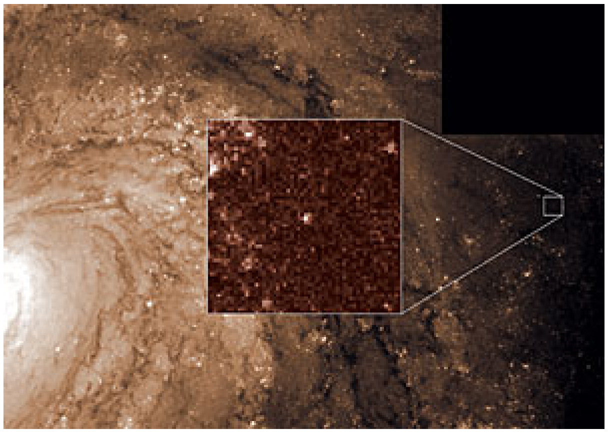


Figure 3: Hubble tracks down Cepheid variable stars in M100

Hubble's high-resolution camera detected and picked out one of the Cepheid variable stars used in this exercise. The star is located in a star-forming region in one of the galaxy's spiral arms (the star is at the centre of the box).

Measurements and calculations

The Period-Luminosity relation for Cepheid variables has been revised many times since Henrietta Leavitt's first measurements. Today the best estimate of the relation is:

$$M = -2.78 \log (P) - 1.35$$

where M is the absolute magnitude of the star and P is the period measured in days. Light curves for the 12 Cepheids in M100 that have been measured with Hubble are shown in Figure 4 and 4a.

Calculating the absolute magnitude

Using the information in these curves, calculate the absolute magnitude M for the 12 stars.

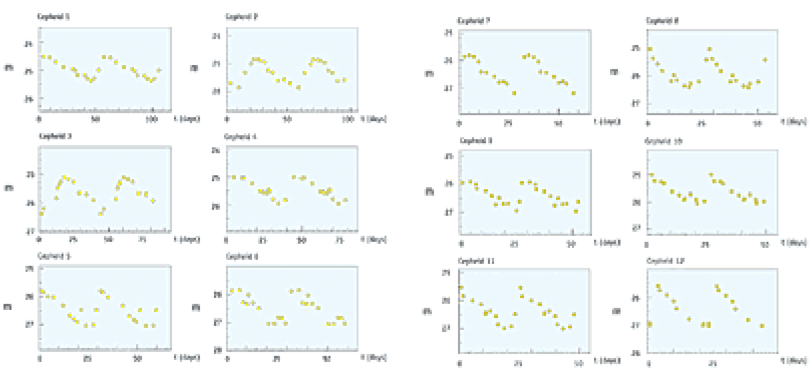


Figure 4 and 4a: Cepheid light curves (click on images for larger versions)

Light curves for the twelve Cepheid variables in M100 that have been observed with Hubble. The absolute magnitude, M, is determined from the period of the Cepheids. Adapted from Freedman et al. (1994).

Calculating the apparent magnitude

Students are first asked to think of a way to determine the apparent magnitude. Either they use their method or they use the one, described by us: At the beginning of the 20th century astronomers measured the minimum apparent magnitude (mmin) and the maximum apparent magnitude (mmax) and then took the average (<m>) of the two.

Calculating the distance to each Cepheid and to M100

For this task the distance equation is used:

$$m - M = 5 \log (D/10) = 5 \log(D) - 5,$$

where D is in parsecs (1 parsec (pc) = 3.086 _ 10^{13} km = 3.26 light-years).

The distances for the twelve Cepheids are not all the same, although the measured stars are located in the same galaxy. The students are asked to find reasons for the differences.

The distance found by scientists is given in the exercises. They took the interstellar dust into account for determining the value and their result is therefore more precise. By comparing the calculated value with the scientists' value, students will see how interstellar matter affects measurements of distances in space.

As a final task the students calculate the Hubble constant and estimate the age of the Universe.

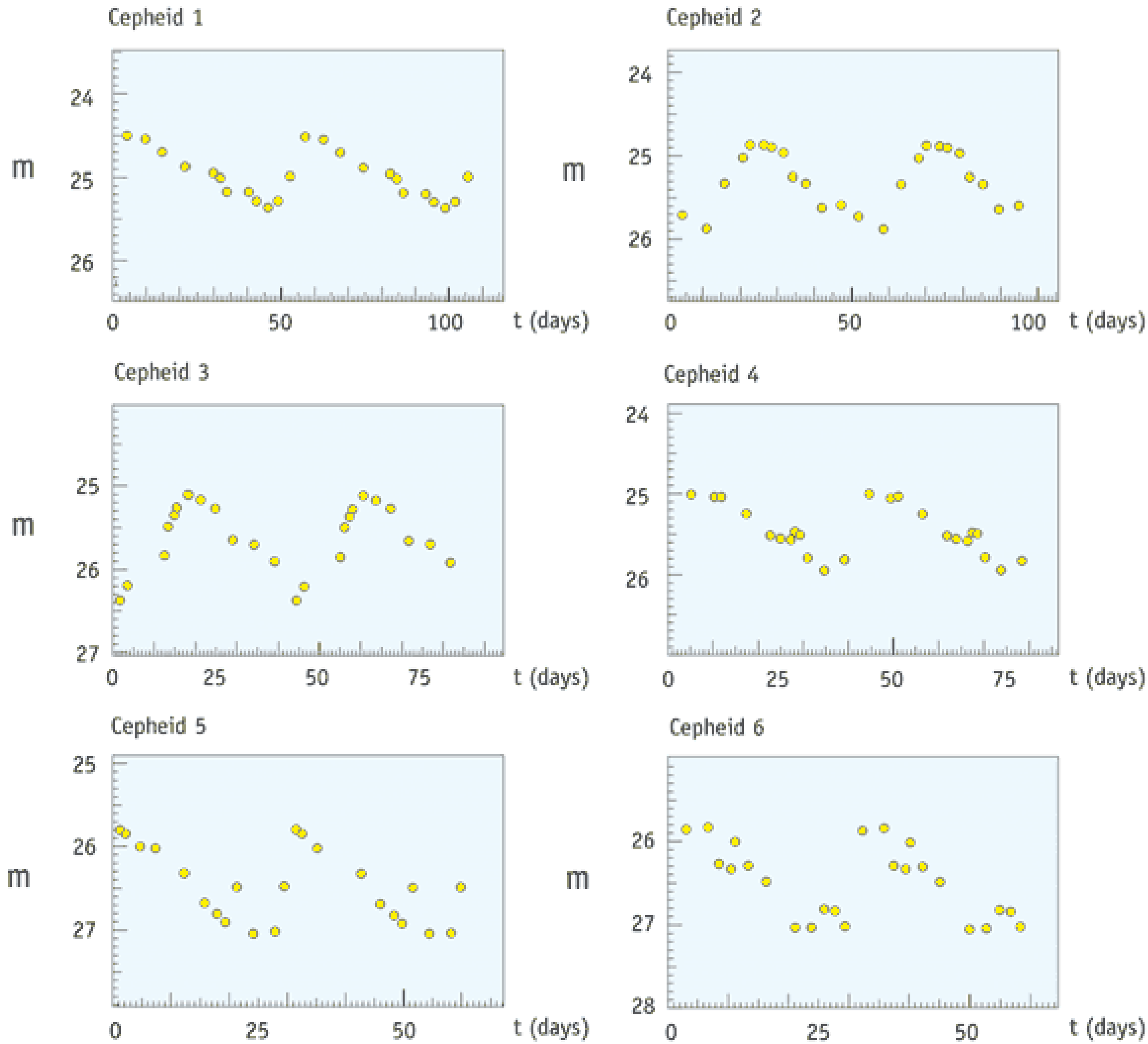


Figure 4: Cepheid light curves

Light curves for the twelve Cepheid variables in M100 that have been observed with Hubble. The absolute magnitude, M, is determined from the period of the Cepheids. Adapted from Freedman et al. (1994).

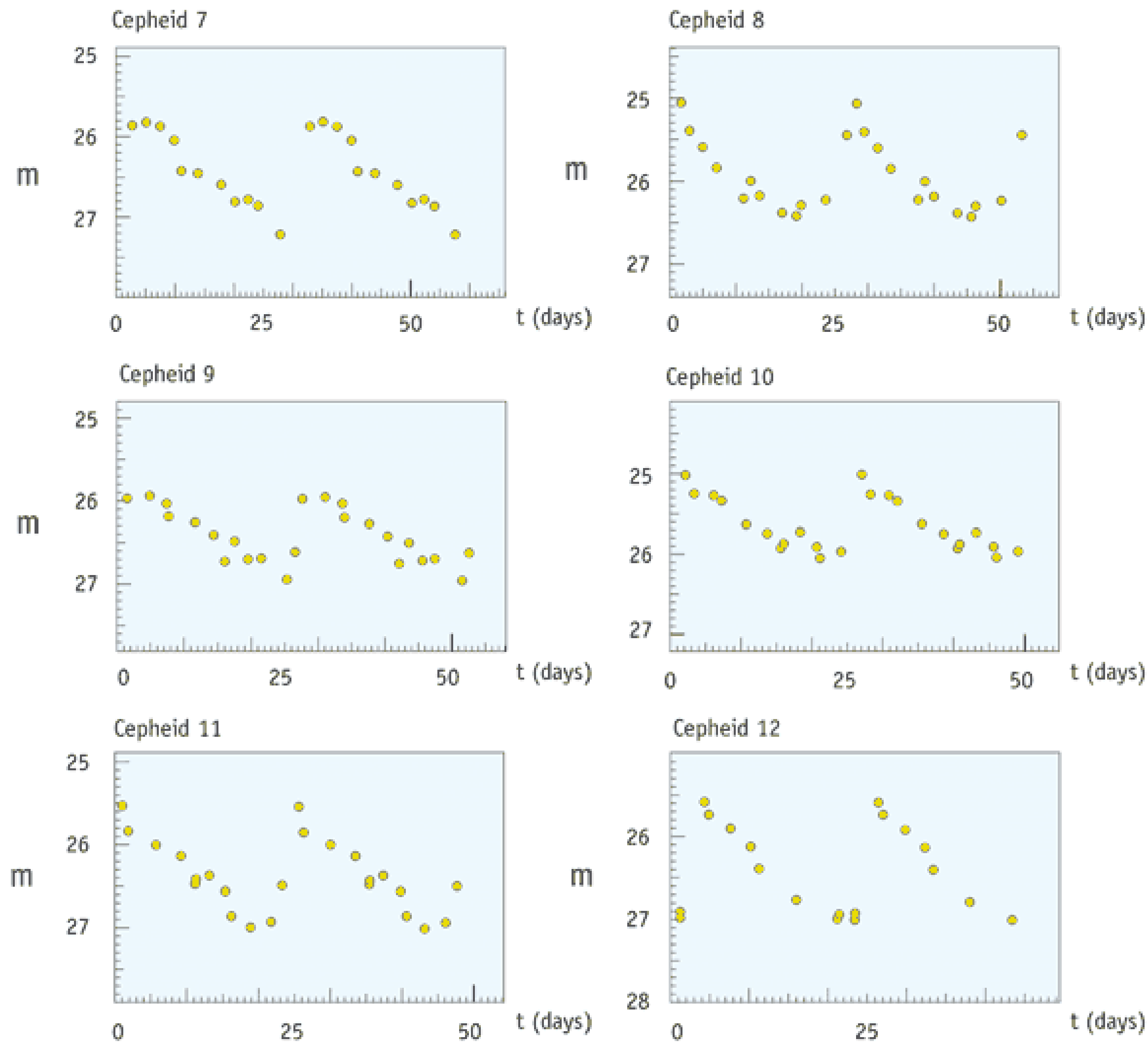


Figure 4a: Cepheid light curves

Light curves for the twelve Cepheid variables in M100 that have been observed with Hubble. The absolute magnitude, M, is determined from the period of the Cepheids. Adapted from Freedman et al. (1994).