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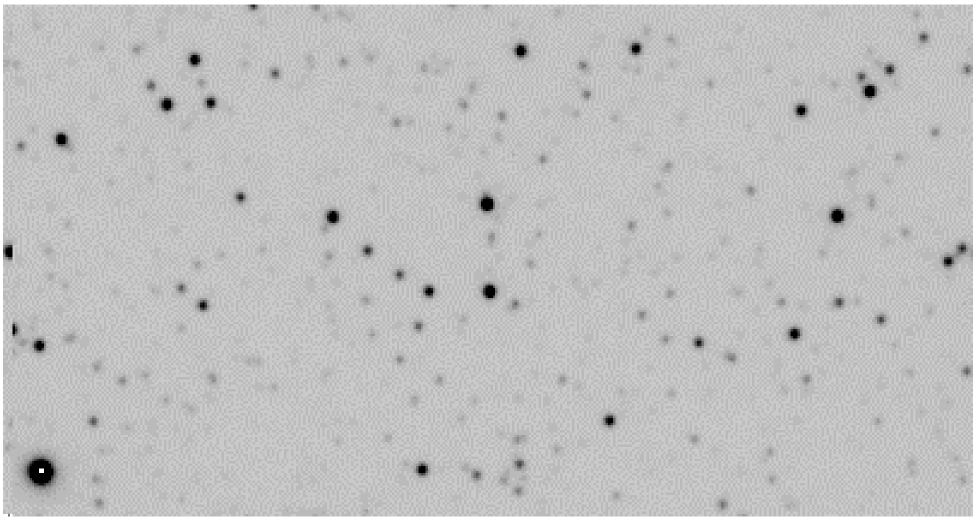
Education and Culture

Measuring the Universe: distances to the Cepheids



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This project has been funded with support from the European Commission.
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Cepheids – the unusual stars

Data needed:

1) Cepheid images – in the catalogue Cepheids
2) Information on the relation between periods of Cepheids and their luminosity (amount of energy radiated by a star in 1 second), Figure 4.
3) Luminosity of the Sun (3.85×10^{26} W)
4) SalsaJ image processing software.

Introduction: It is not easy to measure cosmic distances…

How to measure the distance to the stars? Or to the galaxies? Brightness in not a reliable measure, because two very different objects, one faint but close, and the other bright but very distant, may look the same on our sky. For many centuries astronomers did not even realize that each star is in a different distance from the Earth – they assumed that all stars were located on a single, revolving sphere. In 19th century distances to a few stars were measured by geometrical methods, and this allowed to determine the shape and size of our Galaxy – The Milky Way. Yet immediately a new question arose: are the objects, seen in the night sky as nebulae, located inside our Galaxy, or perhaps they are also separate galaxies, similar to ours? This question was resolved in 1912 by American astronomer, Henrietta Leavitt, who investigated the Cepheids – unusual, pulsating stars. After her discovery the determination of distances to the Andromeda Galaxy and the Large Magellanic Cloud was possible. They turned out to be separate galaxies, different from our Galaxy. Using the data of the stars from Large Magellanic Cloud, we can actually perform similar analysis. We just have to learn the properties of the Cepheids.

Cepheids – the cosmic candles

Cepheids are very bright. Their brightness exceeds the brightness of the Sun by thousand or even ten thousand times. They regularly change their brightness. Each Cepheid is a pulsating star: it periodically changes its size and the surface temperature. The periods are in the range of a few days up to several months. An extremely interesting and useful property of such stars is the relation between their average brightness and pulsation period. Brighter Cepheids pulsate slower than the faint ones. A 3 days period Cepheid emits in a second 800 times more energy than the Sun. A 30 days period Cepheid, is brighter than the Sun by 10 000 times! Measuring the pulsation period of a particular Cepheid, we can determine the amount of emitted energy. When we compare this with the energy reaching our Earth, we can determine the distance of this star. Thus the method of distance determination resembles the method used by someone who can measure the distance to some distant person (in the night!) evaluating the brightness of his torch, provided he knows the real brightness of the torch.

Interestingly, Polaris is also a Cepheid, albeit an unusual one (thus not usable for such method of distance determination).

Necessary formulae

The amount of energy radiated in a unit time by a star is called luminosity, denoted by L. At a distance r, a unit surface perpendicular to the direction of a star receives a flux of energy F:

For example, the luminosity of the Sun is $L_s = 3.85\times10^{26}$ W, and the flux of solar energy reaching a unit surface on Earth is $F_{sun} = 1370$ W/m^2. Thus if we know the luminosity of a star, and measure the energy flux, we can determine the distance r.

Measurements

In order to measure the distance to the Cepheids in the Large Magellanic Cloud a data file for these Cepheids is needed. You can find them in the Cepheids directory. The data were obtained by the OGLE experiment (http://www.astrouw.edu.pl/~ogle/index.html).

The name of each file contains the date of observation. Thus the file CEP-43522-1999-10-24-03-25.FTS is the observation made on 24 October 1999 at 3:23 (you can check the date of observation opening the window Image: show information [HOU-IP: Data Tools/image info]). On all images there is the same part of the sky (see Fig. 1). The location of the Cepheid and comparison stars of constant brightness is shown in Fig. 2. All observations were performed in red and near infrared wavelength.

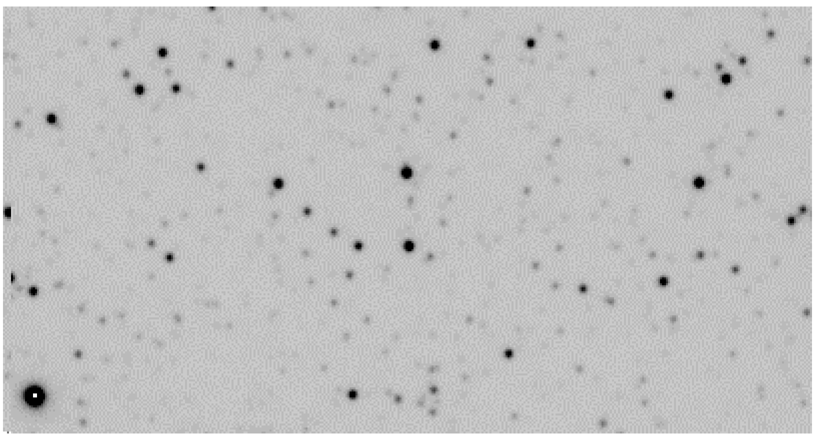


Fig.1. One of the data files with star pictures.

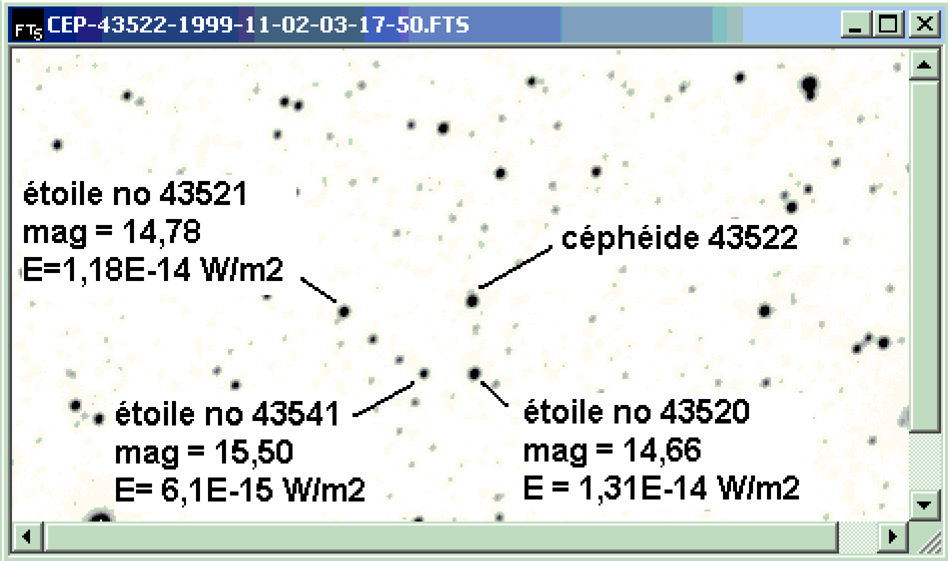


Fig.2 The location of the Cepheids and stars used for comparison.

Observational conditions may be different. The sky could be more or less clear, and the sensitivity of the detectors could vary. The best way to eliminate these unwanted factors in determination of the brightness changes of the Cepheid is comparison of its flux with fluxes of stars of constant luminosity. Different observations of two stars of constant brightness (say, one twice as bright as the other) could give different fluxes, but each time the ratio of their fluxes should be the same (equal two). In the case of an observation of a Cepheid and a constant comparison star, the change of the ratio of their fluxes is the effect of the change of the brightness of a Cepheid only.

Let us start the analysis.

1. Evaluate the brightness of a chosen Cepheid and comparison star in consecutive observations. To do this

    a. Open the data file. Note the date of observation.
    b. Adjust the image in such a way that you can clearly distinguish the stars [Image: Adjust Brightness/Contrast Auto]. Find the Cepheid and the comparison star.
    c. Using Auto aperture tool [Analysis: Photometry; find the star and click on it] measure the brightness of both stars.
    d. Repeat the procedure for all data files.

2. Put the results in a table. Subsequent columns should contain day and hour of each observation, time difference (hours or days) between each measurement and the first one Δt, measured brightness of the Cepheid L_c and of the comparison star L_g , and their ratio L_c/L_g.

time	Δt (days)	L_c	L_g	L_c/L_g
26-09 18:01:00	0.000	168086	357753	0.4698
28-09 19:36:00	2.066	179784	340024	0.5287
…				

3. Calculate average brightness of the Cepheid compared to the comparison star. Using the value of the flux of the comparison star (presented in Fig. 2) and this ratio, calculate the average flux F_{av} from the Cepheid. You can use Excel spreadsheet (appendix 2).

4. Plot the ratio of the fluxes of the Cepheid and the comparison star as a function of time (such a plot is called a lightcurve). Try to fit a sinusoid to the observed changes. Determine the period.

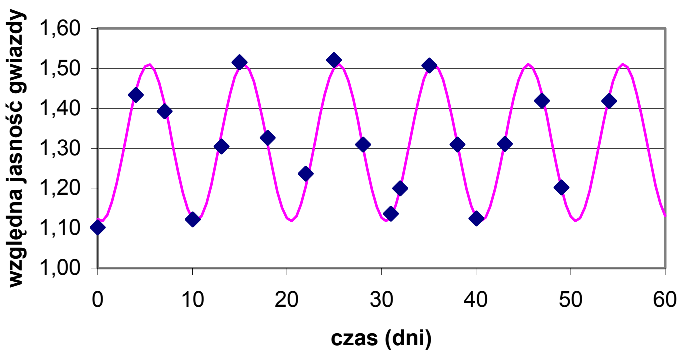


Fig.3 Example of a lightcurve of a Cepheid star

Using the relation between pulsation period and the average luminosity of the Cepheid, presented in Fig.4, find the ratio between the luminosity of the Cepheid and of the Sun. Determine the luminosity of the Cepheid.

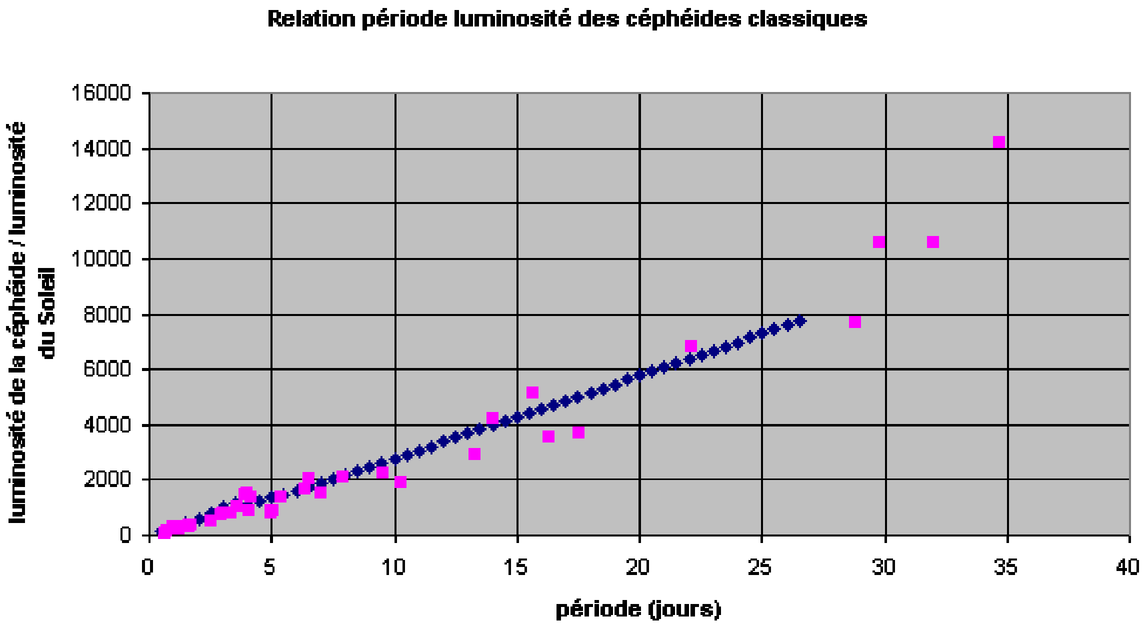


Fig.4 Cepheid luminosity (in solar units) as a function of pulsation period

5. Using the formula given at the beginning of this text, calculate the distance of the Cepheid from the Sun. This is the distance between the Sun and the Large Magellanic Cloud (where the Cepheid is located).

6. Problem: What are the sources of uncertainty of your result? Which of them is most significant? Remember, the results depend on the (unknown) location of the Cepheid within the Magellanic Cloud. Still, as the size of the Large Magellanic Cloud is much smaller than the distance between the Sun and the Magellanic Cloud, this uncertainty does not influence the result very much. There are also other sources of uncertainty. Space between Large Magellanic Cloud and the Earth is filled with small size particles of dust, partially absorbing the radiation. How does this affect the evaluation of the distances?

You can learn more about the Cepheids at those web pages:

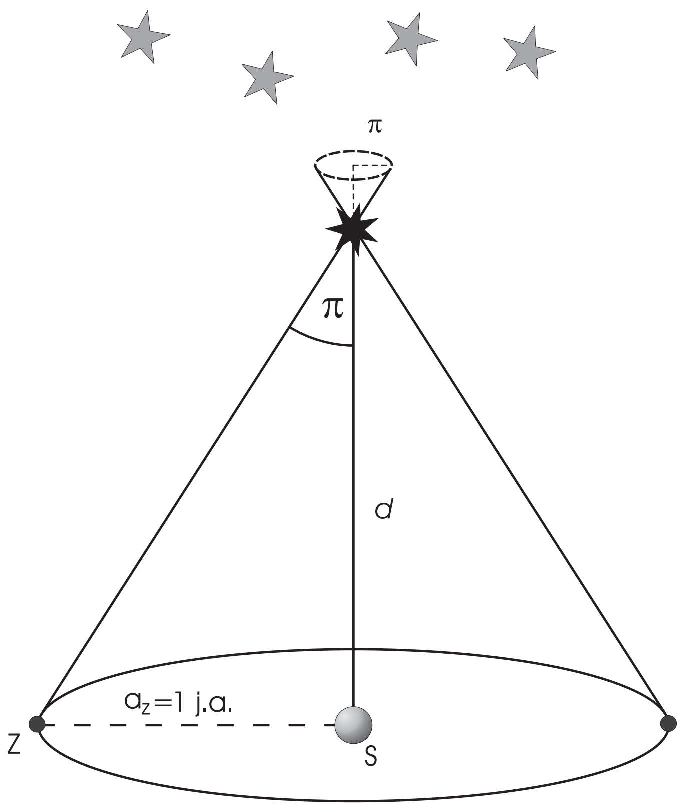
http://sswdob.republika.pl/cefeidy.htm
http://orion.pta.edu.pl/astroex/ex2/cefeidy.html
http://www.uni-sw.gwdg.de/~hessman/MONET/AstroKiste/Sterne/Cepheiden/

Acknowledgments: We are grateful to Fabrice Mottez (CETP) for providing us with the French version of the exercise and to Bohdan Paczyński for continuous encouragement and help with the selection of appropriate data. We thank OGLE team for permission to use their data in the exercise.

Appendix 1. How to measure distances to other galaxies?

The first step, obviously, is the measurement of distances to at least the nearest stars. It can be done by the method of heliocentric parallax.

The effect of heliocentric parallax results in an apparent shift of celestial objects close to us with respect to more distant ones. It is an effect of change of the Earth position in its motion around the Sun. We can observe similar effect looking at some close object in front of the distant one, first with one eye – and then with the other one. We have the impression that the closer object moves.



The effect of parallax. The position of a close star, measured over one year, seems to move against the background of distant stars, along a circle of angular radius π. By measuring π, one can determine the distance to the star.

The first successful measurement of a stellar parallax was performed by Friedrich Bessel in 1838. He measured the distance to 61 Cygni – a faint double star. The next observer, Thomas Henderson, measured the distance to Sirius, and soon afterward the distance to Vega was also determined. The method of heliocentric parallax can be used only for relatively close stars, closer than a few thousand light years (for more distant stars the shift is too small to be measured). Using instruments on spacecrafts, parallaxes – and hence distances – have been measured for thousands of stars, including several hundreds Cepheids. These data improved the calibration of the period–luminosity relation for

Cepheids. The distances to several relatively close galaxies containing Cepheids (with distances of no more than several tens of million light years) could then be measured. The distances to farther galaxies can be determined by observing supernovae.

Appendix 2. Using Excel to determine Cepheid Period

It is not simple to determine the period of a Cepheid when we have only a small number of observations. To do this, you have to

1. Plot the ratio of Cepheid brightness C to the brightness of comparison star R as a function of time $C/R(t)$
2. Try to fit a sinusoid to $C/R(t)$

   .

   This means a determination of four parameters: average Cepheid luminosity B, amplitude of changes A, period P and phase $\Delta\varphi$. It is advisable to first evaluate approximate values of at least some of the parameters.

   a. B –an approximate average of $C/R(t)$
   b. A – half of the \`size' of the plot of $C/R(t)$
   c. Phase – if the first points fall below the average, the phase is negative, e.g. $-\pi/2$ (-1.57), if they lie above – the phase is positive, etc.
   d. Period – you can judge it \`by the eye', but it is usually hard to do.
3. Activate in Excel the function Solver. Input the formula to be fitted, and the preliminary evaluation of the parameters. After a while, Solver will show the result, and the evaluation of quality of fit, or the deviation of fit from data points, Dy^2.
4. Usually such first fit is not very good. Remember (write down!) Dy^2 and start again with a new start value of P.
5. Repeat this procedure, changing the starting period from 1 day to 20 days every 0.1 day.
6. Choose the result with the smallest value of Dy^2
7. Plot the resulting fit with the measurement points $C/R(t)$ and evaluate the quality of the fit \`by the eye'. If the fit looks good enough – use the period for the determination of the Cepheid distance.

Appendix 3. List of the brightest Cepheids

In order to use the results for the Cepheids from this list, you have to:

1. Find the star in the sky, using the coordinates alpha (right ascension) and delta (declination)
2. Determine by yourself the basic pulsation period P0, in days.
3. Use the P-L relation between the Cepheid pulsation period P0 and its luminosity in order to determine the ratio of the Cepheid luminosity L to the luminosity of the Sun, Ls. Note: the plot used in this HOU exercise applies for the Cepheid brightness for the red and infrared light R, and cannot be used for the data given below, which result from visible light V measurements. Hence one has to use the formula given, or the appropriate plot taken from the internet http://web.pdx.edu/~straton/women_cosmology/Day_2_Cepheids.html
4. Cepheids marked as overtone (type FO) are pulsing with a period P1, shorter than the basic period. The basic period (needed in the formula P-L) can be calculated from P1/P0=0.70, or, to a better approximation, P1/P0= P1/P0=-0.027*log(P1)+0.716

P-L relation:

Cepheids with Vav < 8.0mag

star	Period [day]	Vśr [mag]	alpha [h m s]	delta [° ']	ΔV [mag]	Type
SU Cas	1.949322	5.970	2 47 28.88	68 40	0.414	FO
SZ Tau	3.14838	6.531	4 34 20.00	18 26	0.330	FO
Beta Dor	9.842425	3.731	5 33 11.00	-62 31	0.630	
T Mon	27.024649	6.124	6 22 31.00	7 6	1.028	
RT Aur	3.72819	5.446	6 25 21.25	30 31	0.803	
W Gem	7.913779	6.950	6 32 6.00	15 22	0.822	
Zeta Gem	10.15073	3.918	7 1 9.00	20 38	0.480	
MY Pup	5.695309	5.677	7 36 53.00	-48 29	0.301	FO
AH Vel	4.227231	5.695	8 10 26.00	-46 29	0.327	FO
RS Pup	41.3876	6.947	8 11 9.00	-34 25	1.105	
l Car	35.551341	3.724	9 43 52.35	-62 16	0.725	
U Car	38.7681	6.288	10 55 45.57	-59 27	1.165	
ER Car	7.71855	6.824	11 7 31.99	-58 33	0.470	
S Mus	9.659875	6.118	12 10 4.00	-69 52	0.500	
T Cru	6.7332	6.566	12 18 36.50	-62 0	0.498	
R Cru	5.82575	6.766	12 20 52.22	-61 21	0.794	
R Mus	7.510467	6.298	12 39 0.00	-69 8	0.760	
S Cru	4.689596	6.600	12 51 23.56	-58 9	0.690	
V Cen	5.493861	6.836	14 28 56.92	-56 40	0.804	
V737 Cen	7.06585	6.719	14 33 19.86	-61 47	0.317	
AX Cir	5.273306	5.880	14 48 29.86	-63 36	0.420	
R TrA	3.389287	6.660	15 15 16.00	-66 18	0.561	
S TrA	6.323465	6.397	15 56 40.00	-63 38	0.768	
S Nor	9.754244	6.394	16 14 42.00	-57 46	0.640	
V636 Sco	6.796859	6.654	17 19 5.00	-45 34	0.500	
X Sgr	7.012877	4.549	17 44 25.00	-27 48	0.590	
Y Oph	17.126908	6.169	17 49 58.00	-6 8	0.483	

W Sgr	7.594904	4.668	18 1 50.00	-29 35	0.805	
AP Sgr	5.057916	6.955	18 10 0.00	-23 7	0.832	
Y Sgr	5.77338	5.744	18 18 26.00	-18 53	0.725	
U Sgr	6.745229	6.695	18 28 57.00	-19 9	0.717	
BB Sgr	6.637102	6.947	18 48 2.00	-20 21	0.597	
FF Aql	4.470916	5.372	18 56 1.20	17 17	0.321	FO
U Aql	7.023958	6.446	19 26 39.90	-7 8	0.757	
SU Cyg	3.845492	6.859	19 42 48.51	29 8	0.766	
Eta Aql	7.176735	3.897	19 49 55.50	0 52	0.799	
S Sge	8.382086	5.622	19 53 45.00	16 30	0.718	
X Cyg	16.386332	6.391	20 41 26.60	35 24	0.986	
T Vul	4.435462	5.754	20 49 21.00	28 3	0.643	
Delta Cep	5.36627	3.954	22 27 18.53	58 9	0.838	
RX Cam	7.912024	7.682	4 0 49.26	58 31	0.729	
AW Per	6.463589	7.492	4 44 25.00	36 38	0.812	
RX Aur	11.623537	7.655	4 57 55.45	39 53	0.664	
CK Cam	3.29495	7.58	5 2 24.17	55 17	0.6	
AP Pup	5.084274	7.371	7 56 1.00	-39 59	0.647	
AT Pup	6.664879	7.957	8 10 31.00	-36 47	0.904	
V Car	6.696672	7.362	8 27 42.53	-59 57	0.601	
RZ Vel	20.39824	7.079	8 35 18.00	-43 56	1.181	
BG Vel	6.923655	7.635	9 6 39.00	-51 14	0.457	
V Vel	4.371043	7.589	9 20 45.00	-55 44	0.689	
VY Car	18.99	7.443	10 42 33.28	-57 18	1.065	
V898 Cen	3.527125	7.963	11 9 6.80	-54 17	0.4	FO
XX Cen	10.95337	7.818	13 37 1.12	-57 21	0.924	
V381 Cen	5.07878	7.653	13 47 22.49	-57 19	0.720	
BP Cir	2.3984	7.560	14 42 48.00	-61 15	0.337	FO
AV Cir	3.0651	7.439	14 46 9.00	-67 17	0.315	FO
RV Sco	6.061306	7.040	16 55 3.00	-33 32	0.824	
BF Oph	4.06751	7.337	17 2 59.00	-26 30	0.636	
V482 Sco	4.527807	7.965	17 27 31.00	-33 34	0.652	
V950 Sco	3.380090	7.302	17 34 7.00	-40 47	0.365	FO
V350 Sgr	5.154178	7.483	18 42 19.00	-20 42	0.705	
YZ Sgr	9.553606	7.358	18 46 35.00	-16 46	0.674	
TT Aql	13.754707	7.141	19 5 41.40	1 13	1.082	
V496 Aql	6.807055	7.751	19 5 38.60	-7 31	0.349	
U Vul	7.990629	7.128	19 34 26.00	20 13	0.718	
SV Vul	44.994772	7.220	19 49 28.00	27 19	1.054	
V1162 Aql	5.3761	7.798	19 49 35.20	-11 29	0.507	
IR Cep	2.114124	7.784	21 56 19.49	60 46	0.372	FO
V411 Lac	2.908162	7.860	22 26 56.62	50 42	0.3	FO

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