THE QUEST FOR DISCOVERING EXTRAGALACTIC CEPHEIDS

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ABSTRACT.
Chronology of studying extragalactic Cepheids is summarized, and the census of known classical Cepheids and their metal-deficient siblings, the anomalous Cepheids is taken. Up to now (August 2005) about 11000 Cepheids have been revealed in 74 galaxies. Cepheids belonging to the Milky Way galaxy only represent about 6 per cent of the total Cepheid sample.

Key words: Stars: variable: Cepheid; Stars: variable: extragalactic

1. Introduction

Cepheid variables have been in the forefront of observational astronomy for more than two centuries. The first Cepheids were discovered in 1784 when Edward Pigott (1785) revealed variability in the brightness of η Aquilae and John Goodricke (1786) pointed out periodic changes in the brightness of δ Cephei.

One century later, astrophotography became an efficient tool for searching for brightness variability of stars. From 1891 on, hundreds of Cepheids were found in the Magellanic Clouds, based on photographic observations carried out at the Harvard Southern Station in Arequipa (Peru). These historic observations led to the discovery of the famous period-luminosity relationship. Existence of this P-L relation raised Cepheids among the primary distance indicators in establishing the cosmic distance scale.

Another important consequence of these photographic observations is that more Cepheids have been known in either Magellanic Cloud than in our own Galaxy from the beginning of the 20th century. For the sake of historical truth, however, one has to keep in mind that the Magellanic Clouds were not considered to be external galaxies until Edwin Hubble's discovery about nature of the "spiral nebulae". Hubble's seminal result was also achieved with the help of Cepheid variables.

The first external galaxies beyond the Magellanic Clouds known to contain Cepheid variables were M31 and M33 (Hubble 1925a), and NGC 6822 (Hubble 1925b). Discovery of Cepheids in more remote galaxies was extremely difficult in the subsequent decades because those variables had to be detected near the magnitude limit of the photoplates, even if involving the largest available telescopes in the search.

Nearly coinciding with the two hundredth anniversary of discovering the first Cepheids, a new and much more efficient (with respect to photography) wide-field imaging was introduced in astronomy: the CCD era commenced.

In addition to the CCD technique, Hubble Space Telescope (HST) gave another impetus to the projects aimed at discovering and studying extragalactic Cepheids. One of the Key Projects to be carried out with the HST was the determination of the Hubble constant via the precise calibration of the P-L relationship for Cepheids and involving various secondary distance indicators. The detailed description of this calibration and the actual value of the Hubble constant are beyond the scope of this paper, the interested reader is referred to the summary paper by Freedman et al. (2001).

Besides this Key Project, another major survey was performed during the first decade of the operation of the HST. In this project the Hubble constant was determined by calibrating the absolute magnitude of Type Ia supernovae, and the distance to the host galaxies was derived from the Cepheids revealed in the galaxies studied. The final review of this HST related experiment (carried out by Saha, Tammann, Sandage, and their co-workers) is forthcoming.

Researchers dealing with Cepheids concentrated on the reliable calibration of the P-L relation, properly correcting for interstellar extinction (both foreground and in the host galaxy), and metallicity dependence of the Cepheid luminosities, and no survey was published on the census of known Cepheids in the last decade. The latest summary on the observations of extragalactic Cepheids (Jacoby et al. 1992) contains only information available before the launch of the HST.

A state-of-the-art compilation on the census of extragalactic Cepheids has been, therefore, long overdue. Authors of research papers on Cepheids, being unaware of the exact value, usually seriously underestimate the number of galaxies known to contain Cepheids, if such information is mentioned at all.

2. Census of classical Cepheids

For the time being, Cepheids are known in 74 galactic systems. Table 1 is a chronology of finding the first Cepheids in various host galaxies.

In Table 1, the main eras of Cepheid discoveries are separated by horizontal lines. The *classic era* terminated with Hubble's discoveries was followed by a long gap. In the *second* flourishing period Cepheid-hosting galaxies were added to the list at an average rate of one galaxy every second year. The *third era* of extragalactic Cepheid discoveries commenced with the use of HST. It has to be emphasized, however, that ground based optical telescopes were also efficiently used for finding new Cepheids in external galaxies, so the increased rate – about 3 additional galaxies each year (!) – is not solely due to the use of the HST. Quite recently, however, the role of the HST is diminishing in the Cepheid discovery projects.

Some other key events in studying extragalactic Cepheids are also mentioned in Table 1. These remarks appear in brackets following the designation of the relevant extragalactic system. Such milestones are the early discovery of the first anomalous Cepheid (1950), finding the first Cepheids beyond the Local Group (1968), the first Cepheids revealed by applying CCD technique (1986), and the first Cepheids found in the Virgo Cluster (1994).

Nowadays, the new intention of the Cepheid surveys is to reveal as many Cepheids as possible in the nearest galaxies (of various metallicity), in order to carry out a reliable determination of the P-L relationship and to study its universality and dependence on chemical composition. It is, therefore, the number of extragalactic Cepheids which shows an enormous increase recently, instead of the number of the Cepheid-bearing galaxies. Two major optical wide field surveys contributing to the increase of the known extragalactic Cepheids are the projects DIRECT (see Bonanos et al. 2003, and references therein) and Araucaria (Pietrzynski and Gieren 2004).

In order to take a census of known Cepheids, a thorough search was performed in the Cepheid related literature. The results have been summarized in a separate table (posted during the conference). An updated version of the full table will be published in a monograph on Cepheids to be published by Springer (Szabados 2007). That comprehensive table contains information on the number of known Cepheids, the type of the host galaxy, and its membership in galaxy aggregation.

This census was taken for *classical* (i.e. Population I) and the so-called *anomalous Cepheids*. According to the recent evolutionary and pulsation model calculations (Caputo et al. 2004), the anomalous Cepheids are the extreme metal-deficient counterparts of the classical Cepheids. Anomalous Cepheids have been found in numerous dwarf spheroidal galaxies of the Local Group, and also in the metal-poor subsystems of several nearby galaxies which contain classical Cepheids. Owing to their short (0.4-2.4 day) pulsation period, anomalous Cepheids are of lower luminosity than the classical Cepheids which typically pulsate with a longer period. The current photometric magnitude limit does not allow to find anomalous Cepheids beyond the Local Group.

The other varieties of Cepheids have been disregarded here. Type II (formerly Population II) Cepheids clearly differ from classical and anomalous Cepheids in their general properties (mass, internal structure, evolutionary phase).

A shortcoming of this census is that the actual number of known classical Cepheids cannot be given exactly for the nearest galactic systems: in the case of our own Galaxy and the two Magellanic Clouds a lower limit can only be given.

As to the Milky Way galaxy, the problem is caused by the ambiguity hidden in the classification scheme: the known Galactic Cepheids are divided into 6 groups according to the typological classification used by the GCVS: DCEP, DCEPS, CEP, CEP(B), CWA, and CWB. Types DCEP and DCEPS are classical Cepheids of normal and small amplitude, respectively, while double mode (beat) Cepheids belong to the CEP(B) type. When taking the census of Galactic Cepheids, only variables classified as DCEP, DCEPS, and CEP(B) have been considered as classical Cepheids. CWA and CWB stars which denote Type II Cepheids, obviously are not considered here. Stars classified as CEP are, however, problematic because the available information does not allow to decide whether they belong to classical or Type II Cepheids – or they are Cepheids at all. It would be, therefore, unjustified to include them among the classical Cepheids in the census, irrespective of the fact that majority of them may be insufficiently studied classical Cepheids.

The number of known Galactic classical Cepheids was determined from the electronic version of the GCVS, taking into account some recently published additional information. V1359 Aql, V382 Car, V641 Cen, and AF Cru classified as classical Cepheids have been excluded because they turned out not to be Cepheids recently. Moreover, V553 Cas is in fact a classical Cepheid (Berdnikov et al. 1996) misclassified in the GCVS. Evidently several Cepheids in the constellation Doradus, Hydrus, and Tucana located in fact in the Magellanic Clouds have been disregarded. The two known anomalous Cepheids in our Galaxy, BL Boo and XZ Ceti, have been also taken into consideration. Thus the total number of known classical and anomalous Cepheids in our Galaxy is 605. Classification for additional 321 variables (indeterminate types CEP and CEP:) as Cepheids needs confirmation.

Table 1: Chronology of finding the first Cepheids in various host galaxies

Year	Galaxy
1784	Milky Way
1904	Small Magellanic Cloud, Large Magellanic Cloud
1925	NGC 6822, M31, M33
1950	Sculptor (the first anomalous Cepheid)
1967	Ursa Minor
1968	NGC 2403 (first Cepheids beyond the Local Group), Leo II
1971	IC 1613
1976	Draco
1978	Leo I
1982	Sextans A
1984	M81, NGC 300
1985	Fornax, Sextans B, WLM
1986	M101 (first Cepheids revealed by CCD-photometry), Carina
1988	NGC 247, NGC 3109, NGC 7793
1990	NGC 147, NGC 185, DDO 216
1992	NGC 205, IC 4182
1994	NGC 4571 (first Cepheids in Virgo Cluster), NGC 5253, DDO 69
1995	M96, NGC 2366, DDO 155, Sagittarius, Sextans
1996	M100, NGC 925, NGC 4496A, NGC 4536, NGC 4639, IC 10
1997	M95, NGC 3621
1998	NGC 2090, NGC 2541, NGC 4414, NGC 7331, DDO 50, DDO 187
1999	M66, M91, M106, NGC 1326A, NGC 1365, NGC 3198, NGC 3319, NGC 4535, NGC 4603, NGC 4725
2000	NGC 1425
2001	NGC 2841, NGC 3982, NGC 4527
2002	IC 342, And III, And VI
2003	M83, NGC 1637
2004	NGC 4395, And II, Phoenix
2005	NGC 3370

Strangely enough, the classification is easier for extragalactic Cepheids. This situation is due to the fact that photometric data bear information on the shape of the light curve (whose knowledge may not be enough for an adequate classification) and on the mean brightness of the star. Unaware of the distance to an individual Galactic Cepheid, its luminosity cannot be deduced from the photometric data alone. For an extragalactic Cepheid, however, the known distance of the galaxy and the mean brightness of the star allow the determination of the luminosity of the Cepheid, and from the known P-L relationships one can decide whether this value corresponds to a classical or a Type II Cepheid. As to anomalous Cepheids, the situation is not so easy, because their lower luminosity makes their identification more difficult in external galaxies.

Census of the Cepheids in both Large and Small Magellanic Clouds is also uncertain. Ambiguity in the number of Cepheids belonging to Magellanic Clouds is caused by a reason different from the case of our Galaxy. Being the nearest extragalactic systems known to contain Cepheids, Magellanic Clouds are very popular targets, and several major observational projects were carried out without cross-identifying the hundreds of new Cepheids discovered in these independent surveys. The number of Cepheids found and studied in the main microlensing projects is listed in Table 2. Prior to these microlensing projects, 1169 variables were classified as classical Cepheids by the editors of the GCVS in the LMC, and 1167 classical and 35 anomalous Cepheids have been catalogued in the SMC. The huge number of the Magellanic Cepheids (and the small number of the indeterminate Cepheids) is mainly due to Henrietta Swan Leavitt's and the two Gaposchkins'

Table 2: Number of Cepheids discovered/studied in the Magellanic Clouds during the major microlensing projects

Project	Cepheids in LMC	SMC
EROS	290	590
MACHO	~1800	~2000
OGLE	1335	2048

indefatigability. The MACHO data indicate that there are hundreds of anomalous Cepheids among the newly discovered variables in the LMC (Alcock et al. 1999). For denoting the anomalous Cepheids, the abbreviation BLBOO was introduced in the fifth volume of the latest edition of the GCVS, containing the extragalactic variable stars (Samus 1995).

A simple summation of the number of Cepheids ever discovered in either Magellanic Cloud would largely overestimate the actual number of known Cepheids because of the independent rediscoveries of many variables. It is known, for example, that the MACHO sample contains 551 Cepheids already discovered on the early Harvard plates (Alcock et al. 1999). Another example is given by Efremov (2003) who performed a careful cross-identification of the Cepheids discovered during various surveys in two open clusters of the LMC. Unfortunately a complete cross-identification of the Cepheids revealed by various microlensing projects is still missing, but the EROS team has tackled to this work. Taking a risk of mistake, I estimate that the number of known classical Cepheids is about 3000 in each of the Magellanic Clouds.

Ranking the galaxies according to their known Cepheid content, the record holder is the SMC, the second is the LMC, M31 is the third, M33 is the fourth, and the Milky Way Galaxy is placed only fifth. As a matter of fact, the number of known Cepheids in M31 obtained in the census may be a lower limit, too. An et al. (2004) published some important results of the POINT-AGAPE microlensing survey, and it is obvious from their Figure 8 that there are hundreds of Cepheids among the 35 000 variable stars detected in the Andromeda nebula. However, the incomplete information on these variables does not allow to include these Cepheids in the census.

By now (2005 August) *4273 Cepheids* have been detected *beyond the Magellanic Clouds*, 2144 of which are in Local Group member galaxies, and 401 Cepheids in various galaxies belonging to the Virgo Cluster. All these statistical data imply that *Galactic Cepheids represent about 6 per cent of the total Cepheid sample.*

This compilation clearly shows importance of the discovery and study of extragalactic Cepheids.

Acknowledgements. Compilation of the tables was largely facilitated by the use of the on-line databases SIMBAD (CDS, Strasbourg), and the NASA Astrophysics Data System. Financial support from the Hungarian OTKA grant T046207 is acknowledged. The author is indebted to the conference organizers for including this contribution in the scientific program of the meeting in the author's absence.

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