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Introduction

The study of RR Lyrae stars is now a century old. In the closing decade of the nineteenth century, as astronomers subjected the globular clusters to increasingly close scrutiny, they discovered the first of the short-period variable stars today known as RR Lyrae stars. In the course of the ensuing hundred years, the ranks of the RR Lyraes have swelled so that in representatives they outnumber known members of any other well-defined class of variable. Directly or indirectly, investigations of RR Lyrae stars have contributed to almost every branch of modern astronomy:

- RR Lyrae stars have been tracers of the chemical and dynamical properties of old stellar populations within our own and nearby galaxies;
- RR Lyrae stars have served as standard candles, indicating the distances to globular clusters, to the center of the Galaxy, and to neighboring Local Group systems;
- RR Lyrae stars have served as test objects for theories of the evolution of low-mass stars and for theories of stellar pulsation.

In recent years, these and other applications have helped to make the study of RR Lyrae stars a particularly active field and one which seems likely to continue so for the forseeable future.

This introductory chapter has two purposes: first, to provide a brief historical review of the recognition of RR Lyrae stars as a distinct class of variable star, and second, to summarize the salient characteristics of this type of variable. While those already somewhat acquainted with the RR Lyrae stars will find much in this chapter familiar, those with little prior knowledge of these variables will find in it the background needed to appreciate the more specialized topics of subsequent chapters.

1.1 Recognition of RR Lyrae stars as a distinct class of variable star

The latest edition of the *General Catalogue of Variable Stars* (Kholopov et al. 1985) defines RR Lyrae stars as ‘radially pulsating giant A–F stars with periods in the range 0.2–1.2 day and light amplitudes from 0.2 mag to 2 mag [in] V’. Underlying this brief definition are decades of work, commencing, like so much else in the study of variable stars, with the application of photography to the study of the heavens.

The discovery of the first RR Lyrae stars is intimately connected with the realization that some of the stars in globular star clusters are variable stars. The first globular cluster variable to be discovered was a nova which erupted in the cluster M80 in the year 1860. Almost three decades later, in 1889, E. C. Pickering reported the discovery of a second globular cluster variable, a bright variable star near the center of M3. During the following years a few more of the brighter globular cluster variables were found. However, the main story of globular cluster variables, and also of RR Lyrae stars, began in 1893, when Solon I. Bailey initiated a program of globular cluster photography at the Harvard College Observatory station in Arequipa, Peru. In August of that year Williamina Fleming found on Arequipa plates a variable star in the globular cluster ω Centauri. A few days later Pickering found a second variable in the same cluster, and at about the same time, Bailey himself found three variable stars in 47 Tucanae. The discovery of these first Arequipa variables stimulated further searches for variable stars within globular clusters.

In February 1895, Pickering detected six more variables in the globular cluster ω Centauri. That proved to be the start of a flood of discoveries. Between 1895 and 1898 Bailey (1913) searched photographs of 23 globular clusters for variables, discovering more than 500. By the end of this survey, Bailey had discovered almost as many variable stars in globular clusters as had been discovered throughout the remainder of the sky. Variable stars were, however, not equally plentiful in every globular cluster. Bailey noted that, while some globular clusters such as ω Cen, M3, and M5 contained large numbers of variables, others contained few if any variable stars.

Bailey set himself the task of determining periods and lightcurves for the globular cluster variables and, as his work proceeded, it became clear that most of these variables were of a particular type. These variables had short periods of under a day and photographic amplitudes of about 1 magnitude. Moreover, the mean apparent magnitudes of the short-period variables within any given globular cluster were all about the same. These 'cluster-type variables', as they came to be known, were what we should today call RR Lyrae stars.

What was actually the first RR Lyrae star identified? E. C. Pickering's 1889 variable in M3 was probably a Cepheid rather than an RR Lyrae star (Hoffleit 1993). The first RR Lyrae known to occur in a globular cluster may have been found not by Harvard researchers, but by D. E. Packer in 1890. Packer (1890) visually discovered two variable stars in M5, though he did not determine their periods. One of these is now known to be a 26 day period type II Cepheid, but the identity of the second is unclear. E. E. Barnard thought that it, too, was a star later revealed as a Cepheid, but Bailey suspected that Packer had observed a blend of three stars, one of which is an RR Lyrae variable (Bailey 1917). The first RR Lyrae star to be identified outside a cluster may be U Leporis, discovered by J. C. Kapteyn (1890; Hoffleit 1993) and later recognized as a 0.58 day period variable. The paper reporting Kapteyn's discovery was submitted for publication eight days before Packer's first submission. Thus, even were Packer's second variable an RR Lyrae star, technical credit for discovery of the first RR Lyrae variable must go to Kapteyn. The question of who found the first RR Lyrae is, however, mainly a point of curiosity, since whichever was the first RR Lyrae to be found, in consideration of the magnitude of his endeavors, real credit for discovering the class of RR Lyrae stars must go to Bailey. The significance of U Leporis would not be apparent until after Bailey's discoveries of RR Lyrae variables within the globular clusters.

In his paper discussing the variable stars in ω Cen, Bailey (1902) divided the cluster-type variables into three subclasses: Bailey types a, b, and c (figure 1.1). Lightcurve shape was his principal classification criterion. Because these subclasses are still in use

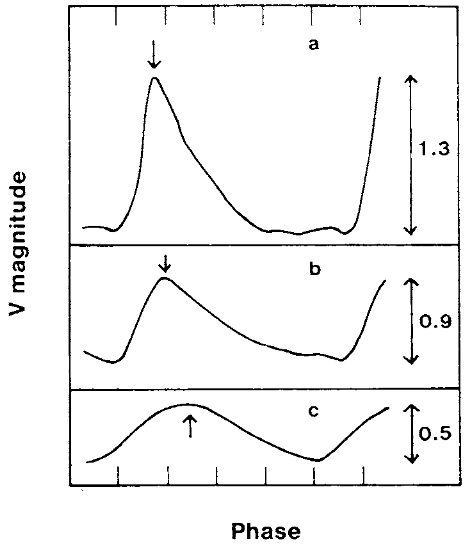

Figure 1.1 The differing lightcurve shapes of RR Lyrae stars of Bailey types a, b, and c.

(though usually simplified to just two types, ab and c, – hereinafter, RRab and RRc, see §1.2.4) it is worth quoting Bailey's original description:

> Subclass a . . . Increase of light very rapid. Decrease rapid, but much less rapid than the increase. Light nearly constant at minimum for about one half of the full period, but perhaps during this time the light changes slowly. In this cluster the range is generally a little more than a magnitude, and the period from twelve to fifteen hours.
>
> Subclass b . . . Increase of light moderately rapid. Decrease is relatively slow and continues with lessening rapidity till about the beginning of increase, except that in some cases there is a tendency to a 'stillstand.' In this cluster, the range is generally a little less than a magnitude, and the period from fifteen to twenty hours . . . This subclass is similar to a, of which it may be regarded as a modification.
>
> Subclass c . . . Light appears to be always changing, and with moderate rapidity. Increase of light generally somewhat more rapid than the decrease, but in a few cases it appears to be of only equal, or of less rapidity. In this cluster the range is generally somewhat more than half a magnitude, and the period from eight to ten hours . . .

Although Bailey was discovering hundreds of RR Lyrae stars in globular clusters, at first few examples of this class were known outside of clusters, in the general field of the Galaxy. The discovery of U Leporis was followed by that of another field RR Lyrae, S Arae, in 1898. Most importantly, W. Fleming, sometime prior to July 1899, discovered a seventh magnitude variable in Lyra which had a period of 0.56 day (Pickering 1901). Pickering noted that in its lightcurve and period this star was indistinguishable from the 'cluster-type' variables. It was given the designation RR Lyrae and it remains the brightest known member of the class. Slowly at first, and then with increasing frequency, more and more of these field 'cluster-type' variables were found. They were initially very important in part because they were nearer and brighter than the variables in globular clusters and so could be studied by techniques such as spectroscopy, which could not then be applied to their faint cluster counterparts. Gradually, the number of field cluster-type stars increased until more of these variables were known in the general field than within globular clusters. As more and more examples were identified outside of globular clusters, the name 'cluster-type' variable no longer seemed appropriate, and the competing term of RR Lyrae star began to be used. Occasionally, other nomenclature is encountered in the early literature, for example, 'antalgol stars', since unlike eclipsing binaries of the Algol-type, many RR Lyraes spend most of their time near minimum rather than maximum light. It was not until the 1948 meeting of Commission 27 of the International Astronomical Union in Zurich that a motion was made by A. H. Joy that 'cluster-type or RR Lyrae-type variables should be called RR Lyrae stars, whether they occur in clusters or in our galaxy'. This motion passed and the name cluster-type variables thereafter faded from the literature.

By about 1915, sufficient data had accumulated concerning the field and cluster RR Lyrae stars to raise the issue of whether they should be regarded as a separate class of variable or included with the Cepheids. Though their periods were shorter, the lightcurve shapes of the RR Lyraes were similar to those of the Cepheid variables. Moreover, spectroscopic studies, especially those of Kiess (1912), indicated that the radial velocity of an RR Lyrae star varied during the course of its light cycle in the same general way as did the radial velocity of a Cepheid. The correct deduction was made, that the basic mechanism of variability was the same for RR Lyrae stars and Cepheids, though at the time of Kiess's study most astronomers still believed that Cepheids were spectroscopic binary stars and that their variability was somehow related to their binary nature. Shapley (1914), in a paper advancing the idea that pulsation was really responsible for the periodic light and radial velocity variations of the Cepheids, concluded that pulsation must also be responsible for the variability of the RR Lyraes. The similarities between RR Lyrae stars and Cepheids encouraged Shapley (1918) to incorporate RR Lyrae stars in his calibration of the Cepheid period–luminosity relation. As tools for measuring the distances to globular clusters, the RR Lyrae stars played a vital role in Shapley's epochal determination of the distance to the center of the Galaxy.

Still, there were reasons for maintaining RR Lyraes as a separate class of variable, rather than subsuming them into the class of Cepheids. Their short periods and their abundance in some globular clusters were, of course, marks of distinction. Hertzsprung (1909; 1913) first pointed out another. Among the field variables, most Cepheids – those which we should now call type I or classical Cepheids – were concentrated to the plane of the Milky Way. The RR Lyraes, on the other hand, were found at all galactic latitudes. In addition, it was found that, unlike most Cepheids, many field RR Lyraes had high radial velocities, a result later confirmed by Joy (1938) from more extensive Mount Wilson observations. These properties we now recognize as indicating that, whereas the classical Cepheids belong to Population I, the RR Lyraes include halo stars of Population II. The high RR Lyrae radial velocities vitiated the argument of Kapteyn and van Rhijn (1922) that the occurrence of field RR Lyraes at all galactic latitudes and their relatively large proper motions implied that the field RR Lyrae stars were faint, relatively nearby, dwarf stars.

Though Eddington (1926) included RR Lyrae in a table of important Cepheid variables in his influential book *The Internal Constitution of the Stars,* others, such as Russell (1927), drew the distinction between Cepheids and RR Lyraes more sharply.

Thus, despite similarities with pulsating Cepheid variables of period longer than a day, the RR Lyrae stars from the first decades of this century were usually looked upon as a distinct class of variable, though one having considerable affinity to the Cepheids. More recently, the realization that all RR Lyrae stars are low-mass horizontal branch stars in the core helium burning stage of evolution has provided an additional argument for distinguishing them from the higher mass classical Cepheids.

There have, however, been adjustments from time to time in the types of variable star included in the class of RR Lyrae stars. A particular confusion arose with the short period pulsating variable stars which are now usually called δ Scuti stars (if Pop. I) or SX Phoenicis stars (if Pop. II), but which have sometimes also been termed dwarf Cepheids, RRs variables, AI Velorum stars, or ultrashort period Cepheids. Reviews of these types of variable star have recently been given by Nemec and Mateo (1990) and Breger (1990). These variables occur within the instability strip below the level of the horizontal branch, near the location of the main sequence. Their periods are short, less than 0.2 days, and their amplitudes in *V* are usually small (but not invariably so). At first, it seemed natural to include these short-period pulsating stars among the RR Lyraes. However, after it was gradually realized that SX Phe and δ Scuti variables differ both in evolutionary state and absolute magnitude from the classical 'cluster-type' variable, it seemed desirable to clearly separate the SX Phe and δ Scuti stars from the group of RR Lyrae variables. The SX Phe and δ Scuti variables will therefore not be discussed further here, and those interested in them are directed to the reviews mentioned above. The location of the RR Lyrae stars in the HR diagram relative to some other well defined classes of variable stars is shown in figure 1.2.

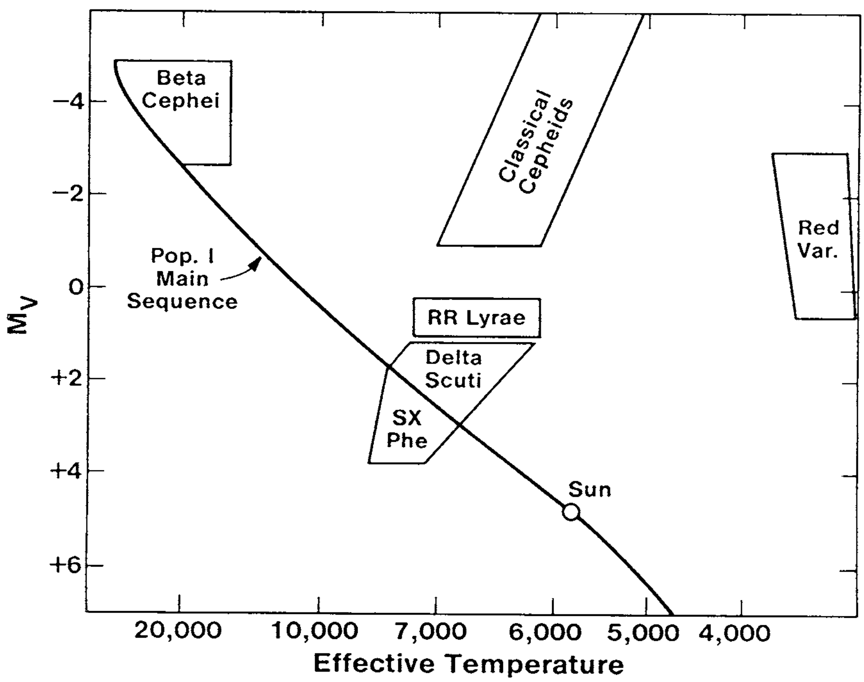

Figure 1.2 The approximate locations in the HR diagram of the RR Lyrae stars and several other well defined classes of variable star.

1.2 Survey of current knowledge

1.2.1 Numbers of RR Lyrae stars

It has been evident since Bailey's pioneering studies that RR Lyrae stars are a relatively common class of variable star. By the late 1980s some 1900 RR Lyrae stars had been discovered in 77 globular clusters of our Galaxy (Suntzeff, Kinman, and Kraft 1991). More than 90 percent of known globular cluster variables are RR Lyrae stars. RR Lyraes are also well represented among the field variables of the Galaxy. These field RR Lyraes are found in the halo of the Galaxy, in the thick disk, and in the galactic bulge. The *Bibliographic Catalogue of RR Lyrae Stars* by Heck (1988) includes data on 6367 RR Lyraes in the general field, most of which are also listed in the fourth *General Catalogue of Variable Stars* (Kholopov et al. 1985). More than a fifth of the 28 457 variable stars listed in this catalog are RR Lyrae stars. More than seven RR Lyrae stars are known for each classical Cepheid or W Virginis star which has been discovered in the Galaxy. Reasonably good lightcurves and periods are available for about 4280 field RR Lyrae stars. Of these, about 91 percent are of type RRab and only 9 percent of type

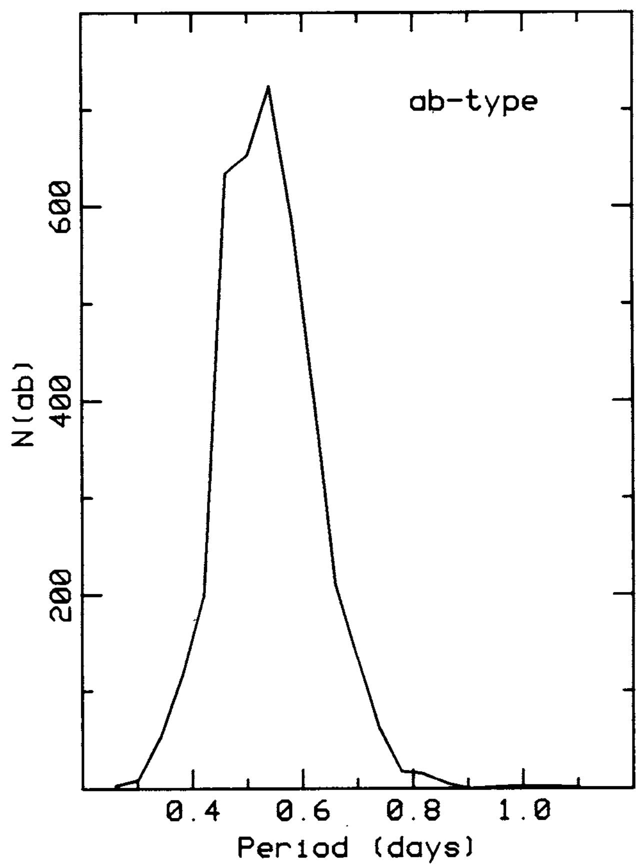

Figure 1.3 Histogram over period for field RRab stars in the Galaxy. Whereas there may be a few RRab stars of greater or lesser period, most have periods between 0.3 and 0.9 days. From Novikova (1988).

RRc. This, however, may not reflect the actual ratio of RRab to RRc variables in the galactic field: the smaller amplitude RRc stars are less likely to be discovered in variable star searches than are the larger amplitude RRab variables. Period distributions of the field RR Lyraes of type RRab and RRc are shown in figures 1.3 and 1.4 (Novikova 1988).

Large though these numbers may seem, only a small fraction of the Galaxy's RR Lyrae variables have been discovered. Suntzeff et al. (1991) estimated that the population of RR Lyrae variables in the halo of the Galaxy between 4 and 25 kpc from the galactic center is about 85 000. The total number of RR Lyraes in the Galaxy, including those in the galactic bulge and in the thick disk, is substantially larger still.

In 1944 Baade announced his discovery of two distinct stellar populations: the Population I stars of the disk and spiral arms, and the Population II stars of the halo and bulge. Most of the RR Lyrae stars of the Galaxy, including the vast majority of those found in globular star clusters, are metal-poor stars in the Milky Way's halo and nuclear bulge, and, initially, it appeared that the RR Lyrae stars could be safely consigned to population II. However, Preston (1959), among others, demonstrated that

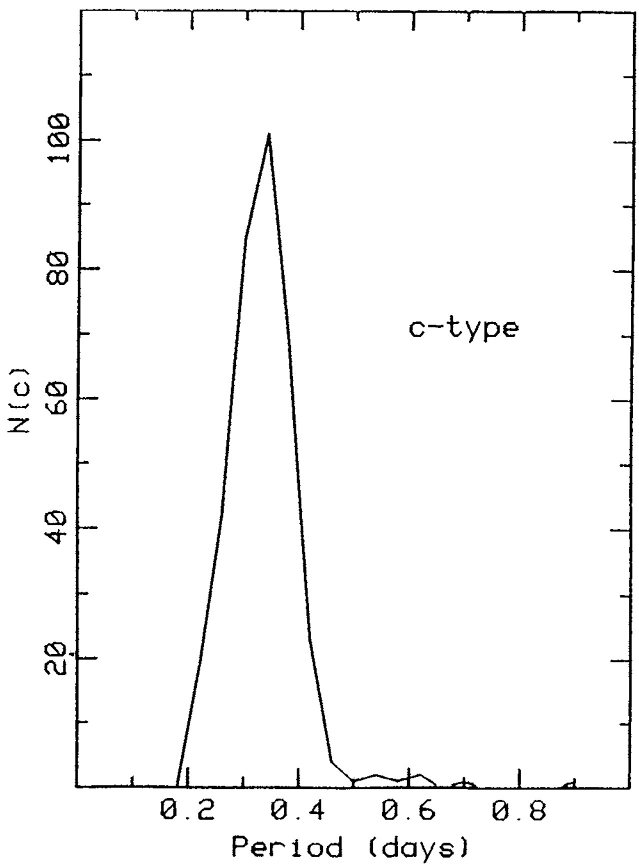

Figure 1.4 Histogram over period for field RRc stars in the Galaxy. While there may be a few RRc variables of greater or lesser period, most have periods between 0.18 and 0.5 days. From Novikova (1988).

the class of RR Lyrae stars actually includes a mixture of population types. He discovered that about 25 per cent of the field RRab stars in the solar neighborhood belong to an old disk population. In contrast to their Population II counterparts, these old disk RR Lyrae stars are only slightly to moderately deficient in heavy elements relative to the Sun, and have a rotation speed about the galactic center of about 200 km/s. These RR Lyrae stars are now believed to belong to the Galaxy's thick disk population (Gilmore, King, and van der Kruit 1990). Relatively metal-rich RR Lyrae stars have also been discovered in the galactic bulge, though most bulge RR Lyraes are metal-poor relative to the Sun.

RR Lyrae stars have been discovered beyond the limits of the Milky Way, first in the Magellanic Clouds and in the Milky Way's companion dwarf spheroidal systems, but recently in more distant Local Group galaxies, including the Andromeda Galaxy. The number of RR Lyrae stars discovered in these systems now exceeds 1500 and is sure to increase considerably .

1.2.2 Mean physical parameters

RR Lyraes are radially pulsating stars, but they are not unstable in the sense that novae or supernovae are unstable. Though they undergo oscillations, these oscillations are excursions around an equilibrium state which does not change significantly on the scale of a human lifetime. In discussing the RR Lyrae stars, it thus makes sense to consider that equilibrium state, as represented by measurements of the mean physical characteristics of the variables. Devising a satisfactory method of averaging observed properties over the pulsation cycle to arrive at the 'equilibrium' equivalent is often a difficult task.

Considerable effort has been devoted to determining the average physical parameters of stars of the RR Lyrae class. In part, this has been driven by the realization that RR Lyrae variables might be very useful as standard candles in distance determinations. Representative recent results are summarized in table 1.1. A caution is in order. Although this table summarizes much recent research concerning RR Lyrae stars, our knowledge of the physical parameters of these variables is in many ways incomplete. Each of the entries stands in need of some qualification.

Absolute magnitude

Since Bailey's early work, it has been known that the RR Lyrae stars in any given globular cluster show only a small range in mean brightness. This raised the possibility that all RR Lyrae stars might have about the same absolute magnitude, and hence that they might be excellent standard candles for the determination of distances. It is of course necessary that the absolute magnitudes of the RR Lyrae stars be determined in some fashion before their potential as standard candles can be realized.

The long and still unfinished search for the absolute magnitudes of the RR Lyrae variables is the subject of chapter 2 of this monograph. No RR Lyrae is near enough to have its distance, and thus absolute magnitude, directly measured by the technique of trigonometric parallax (though with the increasing accuracy of parallax determinations, such as may be obtained from the Hipparcos satellite, this may change in the future). Hence, the techniques used to measure RR Lyrae absolute magnitudes have been more indirect. Three basic approaches have been tried: statistical parallaxes, Baade–Wesselink solutions, and the determination by various independently calibrated

Table 1.1. *Properties of RR Lyrae stars*

Period	0.2–1.1 days
$\langle M_v \rangle$	$+0.6 \pm 0.2$ (metal-poor stars)
$\langle T_e \rangle$	7400 K–6100 K
$\langle \log g \rangle$	2.5–3.0
[Fe/H]	0.0– −2.5
Mass	$\approx 0.7\ M_\odot$
Radius	≈ 4–$6\ R_\odot$

methods (Cepheid period–luminosity relations, main sequence fitting, etc.) of the distances to systems which contain RR Lyraes. The value $\langle M_v \rangle = +0.6 \pm 0.2$ in table 1.1 spans most recent determinations for metal-poor RR Lyrae stars, which generally range between +0.4 and +0.8. However, all RR Lyrae stars may not share exactly the same absolute magnitude and there has been much recent discussion as to whether RR Lyrae absolute magnitudes are a function of metallicity. There is substantial evidence that metal-rich RR Lyrae stars are less luminous than metal-poor RR Lyraes. The size of this difference in luminosity is a matter of controversy, but may amount to as much as a few tenths of a magnitude between stars differing by a factor of ten in heavy element abundance.

Surface temperature

As indicated in figure 1.2, stars of the RR Lyrae type are confined to well-defined limits in the HR diagram. These limits have been defined by observations of RR Lyrae stars both in the general field of the Galaxy and in globular star clusters. Average values of effective temperature and surface gravity have usually been calculated from application of model stellar atmospheres to multicolor photometry or from spectroscopy of those stars. Model atmospheres do not of course give a perfect representation of real stars and various systematic errors can occur in this process. For example, the hottest RR Lyrae stars (of type RRc) appear to have a mean effective temperature near 7400 K and the coolest RR Lyrae stars (of type RRab) appear to have a mean effective temperature near 6100 K, as indicated in table 1.1. However, these limits are subject to some uncertainty. Different color–temperature relations in the recent literature yield effective temperatures for the hottest and coolest RR Lyrae stars which differ by as much as 300 K from the values given above. It may be that those values are too high, perhaps by 100–200 K. The temperature width of the RR Lyrae instability strip, about 1300 K, is perhaps subject to less uncertainty. Similar uncertainties affect the derived values of surface gravity, $\langle \log g \rangle$, which, though certainly approximately correct, may be uncertain by a few tenths in the logarithm.

Chemical composition

When one measures the chemical composition of a star, either by multicolor photometry of its light, or by analysis of its spectral lines, one is actually measuring its surface, photospheric composition. In the case of relatively low-mass stars, such as those which become RR Lyrae stars, nucleosynthesis of significant amounts of elements heavier than carbon and oxygen is not expected during the lifetime of the star.

Thus, the measured abundance of heavy elements in the atmosphere of an RR Lyrae star is believed to reflect the abundance of heavy elements in the interstellar gas cloud from which that star formed. It is this property, together with their considerable age, which make RR Lyrae stars useful tracers of chemical history.

RR Lyrae stars are observed to differ considerably in chemical composition, particularly in their photospheric abundances of the elements heavier than helium ('metals' in astronomical parlance). As noted above, many RR Lyrae stars belonging to the old disk population of the Galaxy and some (but not all) of those found in the galactic bulge are only modestly deficient in heavy elements relative to the Sun. Some may be as metal-rich as the Sun and others perhaps even more so. On the other hand, those RR Lyraes found in the galactic halo can be very deficient in heavy elements.

To characterize the overall heavy element abundance of stars, astronomers often employ the [Fe/H] notation. In this notation, the ratio of iron to hydrogen in the photosphere of one star is related to that ratio in another star, usually the Sun: [Fe/H] $= \log(\text{iron/hydrogen})_* - \log(\text{iron/hydrogen})_\odot$.

In this notation, the metal rich RR Lyraes are near, but usually somewhat below, [Fe/H] = 0.0, and the most metal-poor RR Lyraes are near [Fe/H] = −2.5, deficient in iron by a factor of 300 relative to the Sun. The [Fe/H] notation is a useful shorthand, which will be employed extensively in this book, but it must always be remembered

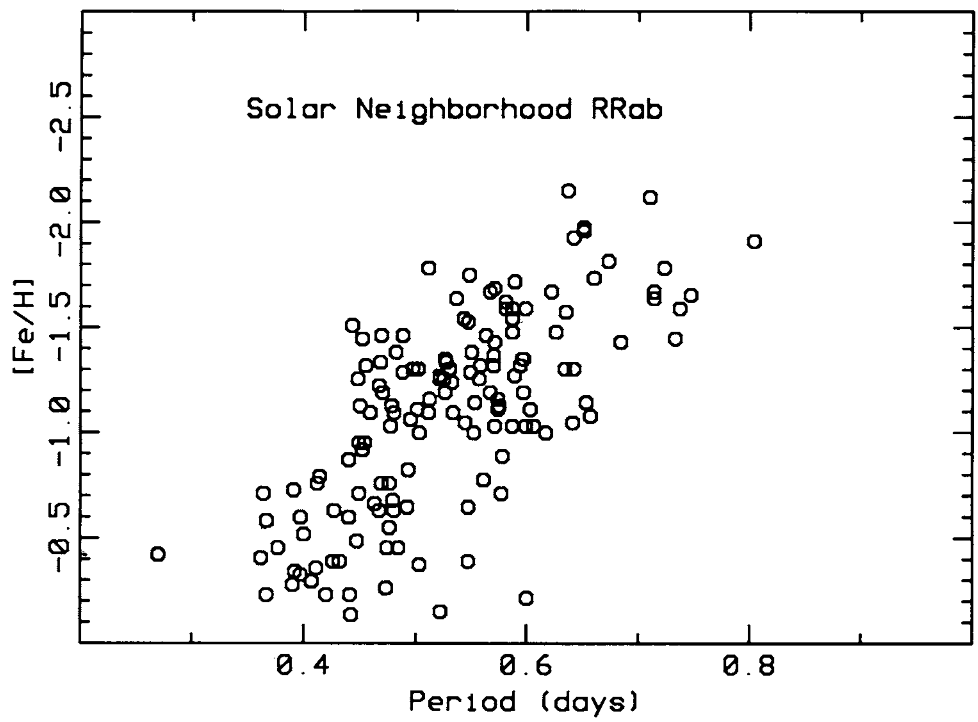

Figure 1.5 The relationship between [Fe/H] and period for field RRab stars in the solar neighborhood. The existence of a general correlation between period and metallicity for these stars is shown, with the more metal-rich RRab stars tending to have shorter periods. The metallicities are from diverse sources, but mainly from ΔS measurements. The metal abundance scale is that of Butler (1975).