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Asteroseismology of γ Doradus Variables: Past, Present, and Future

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Abstract

In this paper, we present the current state of research of the γ Doradus phenomenon, review past work, and look towards possible future research opportunities. Although published observations have not yet yielded enough information for explicit asteroseismological solutions, recent space-based missions, coupled with intense, coordinated ground-based support and continued advances in the theoretical understanding of these variable stars will likely allow us to probe stellar interiors in the next several years.

The Past

More than 40 years ago, Cousins & Warren (1963) published a paper announcing the variability of γ Doradus. Future papers would identify other "variables without a cause," all with spectral types close to F0 and luminosity classes of V, IV-V, or IV. Because of their unique place in the colour-magnitude diagram [overlapping the red (cool) edge of the δ Scuti instability strip and extending to redder colours], the specific physical mechanism causing the observed variations remained a contentious subject [see Abt, Bollinger & Burke (1983); Krisciunas et al. (1993); Zerbi, Mantegazza & Poretti (1994); Mantegazza, Poretti & Zerbi (1994); Balona, Krisciunas & Cousins (1994); Hatzes (1998)].

Early efforts at producing a catalogue of these variables for use by the community proved to be difficult, since their discovery was usually incidental to other efforts; stars with "mistaken identities" were still catalogued, but were relegated to a "Stars Formerly Under Consideration" (SFUC) list [see, e.g., Kaye, Henry & Rodríguez (2000; misclassified δ Scuti star) and Paparó et al. (2000; binary system tidal effects)]. Despite these minor setbacks, the γ Dor variables were defined as a class by Kaye et al. (1999a) who, based on informal discussions at a conference held in 1995 at Cape Town, South Africa (Stobie & Whitelock 1995), and upon several papers in the literature (e.g., Krisciunas et al. 1993; Balona et al. 1996; Zerbi et al. 1997a, 1997b; Poretti et al. 1997; Kaye 1998a; Kaye et al. 1999b), defined the class to consist of "variable stars with an implied range in spectral type A7–F5 and in luminosity class IV, IV-V, or V; their variations are consistent with the model of high-order (n), low-degree (ℓ), nonradial, gravity-mode oscillations."

The Present

Since Cousins & Warren's paper in 1963, more than 100 papers have been published on various observational aspects of γ Dor variables[1]. As of the date of this meeting, the number of "bona fide" γ Dor stars stands at 54 (Henry, Fekel & Henry 2005). In addition to the continuous serendipitous discoveries, there have been a large number of dedicated searches for these variables.

[1] The figure of 100 papers includes actual γ Dor variable discovery papers, analysis of data revealing the presence (or absence) of γ Dor stars, database searches for γ Dor stars, and an estimate of the large number of papers that discuss data analysis techniques relevant to these stars. This list of references, considered to be tentatively complete through June 2006, may be requested from the author.

Database mining has resulted in the discovery of some γ Dor stars [including, e.g., the *Hipparcos* catalogue (Handler 1999); the Geneva Photometric Database (Eyer & Aerts 2000); and the R00 Catalogue (Rodríguez & Breger 2001)]; a number of space missions have retrieved data on γ Dor variables [including the Canadian MOST satellite; see Matthews (2007)], several space missions are likely to find even more [e.g., COROT (Mathias et al. 2006) and WIRE (see Bruntt, 2007)]; and ground-based networks have provided insights that no single observing site could reveal alone [e.g., the Whole Earth Telescope and the Delta Scuti Network; see Breger et al. (1997)].

Early studies suggested that the γ Dor phenomenon may be restricted to younger stars (Krisciunas et al. 1995b), and since then, more than 15 studies of clusters from NGC 6231 (Arentoft et al. 2001; $\log t \sim 6.8$) to the Pleiades (Martín & Rodríguez 2000; $\log t \sim 8.1$) to NGC 2420 (Kim et al. 2001; $\log t \sim 9.0$) support the claim that the γ Dor phenomenon is limited to stars younger than $\log t = 8.4$ (see the discussion in Kim et al. 2001).

A collection of some of the most notable γ Dor variables includes the following:

Variable star class namesake: γ Doradus[2] (Cousins & Warren 1963)

Brightest γ Dor star in the Northern Hemisphere: 9 Aurigae (Krisciunas & Guinan 1990)

γ Dor stars with identified pulsation modes: γ Doradus (Balona et al. 1996), 9 Aurigae (Aerts & Krisciunas 1996), HD 207223 (Aerts & Kaye 2001), HD 12901 (Dupret et al. 2005a; see also Moya et al. 2005), HD 48501 (Dupret et al. 2005a; see also Suárez et al. 2005)

Chemically peculiar (λ Boötis-type): HR 8799 (Gray & Kaye 1999)

Chemically peculiar (Am-type): HD 8801 (Henry & Fekel 2005), HD 100215 (Grenier et al. 1999), HD 221866 (Kaye, Gray & Griffin 2004)

Part of a confirmed binary system: HD 7169 (Fekel et al. 2003), HD 19684 (Henry & Fekel 2002), HD 23874 (Fekel et al. 2003), HD 62454 (Kaye et al. 1998b), HD 86358 (Henry & Fekel 2003), HD 100215 (Griffin 2006), HD 105085 (Henry & Fekel 2003), HD 113867 (Henry & Fekel 2003), HD 160295 (Henry & Fekel 2003), HD 167858 (De Cat et al. 2006), HD 209295 (Handler et al. 2002), HD 221866 (Kaye, Gray & Griffin 2004)

Also show *p*-mode pulsations: HD 8801 (Henry & Fekel 2005), HD 209295[3] (Handler et al. 2002)

It is interesting to note that although HD 8801 is reported to be an Am star (Henry & Fekel 2005), it is *not* among the list of confirmed binary γ Dor stars. If this is verified, HD 8801 will be a *very* unique object, showing both γ Dor and δ Sct variations as well as being one of a very few single Am stars (see Abt 1961, Abt 1965, and the more recent discussions in Noels, Montalbán & Maceroni 2004 and references therein). For completeness, we note that the MOST mission has tentatively reported the discovery of two similar stars (Matthews, 2007).

[2] In addition to being the variable star class namesake, γ Doradus is the brightest star in the class ($V = 4.24$).

[3] At least some of the *g*-mode variations in HD 209295 are driven (or even amplified) by the tidal interactions between the two stars in this binary system (Handler et al. 2002).

Theoretical Aspects

While observers had a large head-start on theorists, theorists have also contributed a tremendous amount of work in this field. Between 1998 and the date of this conference, roughly 27 papers have been published on various theoretical aspects of γ Doradus stars. A detailed review of this work is provided by Dupret et al. (2007), but a short summary is provided here:

- The first discussion of the γ Dor *g*-mode driving mechanism was published by Guzik et al. (2000).
- The first purely theoretical instability strip for γ Dor stars was published by Warner, Kaye & Guzik (2003).
- A revised theoretical instability strip using time-dependent convection was published by Dupret et al. (2004).
- The discussion of the importance of convection-pulsation coupling in γ Dor stars was published by Dupret et al. (2004, 2005b)
- The seventeenth international conference on stellar pulsation was held in Rome in June 2005; the proceedings of that conference were published in 2006 as volume 77 of the *Memorie della Societá Astronomica Italiana*. A significant portion of that volume contains cutting-edge research (including theoretical work) of γ Dor and δ Sct stars.

The Future

There has been a great deal of work done on γ Dor stars, and the results of progress reveal more information about this variable star class each year. There are, however, a number of issues that we still do not understand; four of the larger issues are discussed below[4].

Edges of the instability strip

As has been discussed in many papers, the number of known *bona fide* γ Dor stars is small (cf. the number of known δ Sct stars). This fact in and of itself makes it difficult to "map" the edges of the γ Dor instability strip by simply plotting each member on a colour-magnitude diagram [again, cf. the case for δ Sct stars; see Breger (1979)]. Several attempts have been made [see, e.g., Handler & Shobbrook (2002) and Henry & Fekel (2005)], but there are simply not enough objects to set "firm" instability strip boundaries based on observations (again, cf. Fig. 2 in Breger 1979 and Fig. 8 in Rodríguez & Breger 2001).

Temporal dependence/stability of pulsation modes

Some γ Dor stars show clear evidence of modes that are unstable over the course of several observing seasons. In this case, the term "unstable" is used to indicate modes that do not appear reasonably regularly from one observing season to the next. While some may suspect that this is due to the intrinsically difficult nature of analysing γ Dor data, this particular issue has been verified with double-blind tests using different software and different analytical and numerical techniques on the same sets of data. Interested readers are encouraged to examine the published literature on 9 Aurigae (see, e.g., Krisciunas et al. 1991; Krisciunas et al. 1993; Zerbi, Mantegazza & Poretti 1994; Mantegazza, Poretti & Zerbi 1994; Balona, Krisciunas & Cousins 1994; Krisciunas et al. 1995a; Aerts & Krisciunas 1996; Balona et al. 1996; Zerbi et al. 1997a); in addition, more than 10 years of BV differential photometry is now available on this object, yet the temporal dependence of the various modes is not understood.

[4] The "mystery" of HD 8801 and the recently discovered similar objects are discussed in the previous section.

Additional scatter at times of maximum brightness

In several γ Dor variables, there is clear evidence of "extra" scatter at the time of maximum brightness that some liken to the Blazhko effect seen in RR Lyrae stars; the most often-cited (and thus, likely most extreme) example of this is HR 8799 (Zerbi et al. 1999) in which the additional scatter may be large compared to the observational scatter in other portions of the phased light curve (see, e.g., Fig. 1, below and Figs. 2, 8, 10, 14, 16, and 20 in Henry, Fekel & Henry 2005). Although this particular issue has not received a great deal of attention to date, it may be related to the temporal stability of the pulsational modes (see above) and thus be used to more fully understand this class of variable stars.

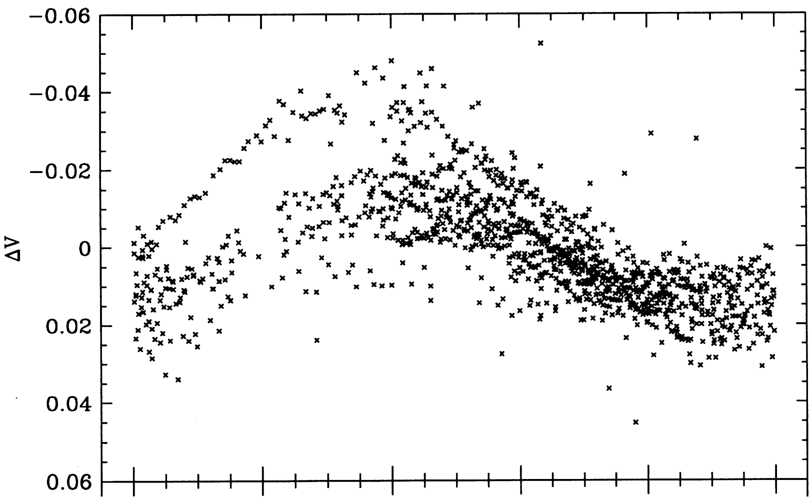

Figure 1: Johnson V light curve phased using the primary period of HR 8799 showing the "extra" scatter at the time of maximum brightness (from Zerbi et al. 1999; see text for details).

Presence and role of magnetic fields

An early study by Kaye & Strassmeier (1998) on the Ca II H&K lines in a collection of γ Dor stars reported that there was no significant chromospheric activity in any of the observed stars. Since the debate regarding the physical mechanism causing the variability of these stars was coming to a close and large starspots were being ruled out, this subject seemed moot. However, the driving mechanism of the gravity modes in these stars is linked directly to the thin convective shell in the outer portion of the star (see Guzik et al. 2000 and Dupret et al. 2004). The fine structure of this convective shell could potentially be affected by differential rotation (that would then result in a non-negligible dynamo-produced magnetic field). Since γ Dor stars are hot compared to "typical" spotted stars (e.g., RS CVn and BY Dra stars), the cores of the Ca II H&K lines are washed out. A more useful indicator of chromospheric activity (and therefore of magnetic fields) is the He I D_3 triplet at λ5876Å [for details, see Wolff, Heasley & Varsik (1985), Wolff, Boesgaard & Simon (1986); Rachford & Canterna (2000); Rachford (2000)]. A collection of high-SNR, high-resolution spectra in the λ5876Å region is in hand for a number of northern-hemisphere γ Dor stars, including a time series of spectra for 9 Aurigae.

The Path Ahead

The future of γ Doradus research is bright. In addition to planned space missions dedicated to asteroseismology, there are new asteroseismological collaborations being formed each year. As a community, we continue to grow and thrive. George Mason University has recently completed the construction of a new on-campus observatory and will install a new 0.8-meter telescope within the next 18–24 months. Plans for this telescope revolve around asteroseismology, and the potential for new collaborations with nearby institutions are promising. Farther-reaching collaborations with other individual institutions and with larger organizations like HELAS to form more complete networks will continue to bring the community together and to enhance the understanding of γ Doradus and related objects.

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DISCUSSION

Matthews: MOST has found a number of γ Dor stars and candidates among its guide stars and Michael Gruberbauer in Vienna is working on these as part of his Master's thesis. We've also found at least two hybrid stars with both γ Dor and δ Scuti pulsations. Concerning HD 8801 you asked whether it was incomplete or just odd. The first of our two hybrids was classified as an Am star and it shows an oscillation spectrum very much like the Henry & Fekel star: oscillation modes in three groups, although we see more frequencies. We got spectra for the other one and it's also an Am star. We don't know enough to rule out any long or short-period spectroscopic binarity, but it's intriguing that there a now three potentially single hybrid pulsators and all three of them are Am stars. So there may be a pattern emerging but I certainly agree with your opinion that all of them need more follow-up work for mode identification but also to rule out binarity.

Harry Shipman, Mike Montgomery, Tony Kaye and Ian Roxburgh at the conference dinner, with John Bohannon (= "Mr. Kolenberg") in the background.