WHITE DWARF PULSATIONS: A REVIEW

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I. INTRODUCTION

The DA white dwarfs are those which show only the Stark-broadened lines of hydrogen in their spectra. They comprise about 80% of the total white dwarf population. A subset of the DA dwarfs, the ZZ Ceti stars, form a highly homogeneous class of nonradially pulsating variable stars. In this paper we shall review the observations from which both the physical properties of the stars and the characteristics of the pulsations have been derived. Data obtained since the last review of these variables (Robinson 1979) is stressed, as these data are forcing a somewhat revised understanding of the ZZ Ceti stars and their relationship to investigations of white dwarfs and to pulsating variable stars, in general.

Pulsations and nonradial pulsations in particular, are ubiquitous among stars. They occur in β Cephei stars (cf. Jerzykiewicz 1980), line profile B stars (Smith 1980), δ Scuti stars (Breger 1980), the white dwarf components of some cataclysmic variables (Chanmugam 1972, Warner and Robinson 1972), the sun (cf. Hill 1980), and the ZZ Ceti stars. The intent of this review will be to point out that because of past (and potential future) rapid advances in our understanding of ZZ Ceti stars, these variables are the best basic "laboratory" for the investigation of pulsations in a wide variety of stars.

II. PHYSICAL PROPERTIES OF ZZ CETI STARS

The history of the ZZ Ceti stars is brief, beginning in 1968 with the discovery by Landolt (1968) of light variations with a quasi-period of about 750 s and an amplitude of about 0.3 mag in the DA white dwarf HL Tau-76. Early systematic surveys for photometric

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variations in white dwarfs, planetary nebula central stars and related objects were begun by Hesser and Lasker and their collaborators in 1969. They discovered luminosity variations in the DA dwarf Ross 548 which appeared to have two periods of about 213 and 273 s simultaneously present in its light curve, with a total amplitude of about 0.01 mag. They also noted the similarity in color of R548, now known by the variable star name ZZ Ceti, to HL Tau-76 (Lasker and Hesser 1971). The discovery by Schulov and Kopatskaya (1973) of luminosity variations in the white dwarf G29-38, again a DA dwarf with colors very similar to HL Tau-76 and R548, spurred the observational efforts to date, which have resulted in the discovery of an additional 14 luminosity variable white dwarfs. The known variables, all of spectral type DA, are listed in Table 1 along with the 1950 coordinates, the Johnson V magnitude and colors primarily extracted from the fundamental series of papers on white dwarfs by Eggen and Greenstein (Eggen and Greenstein 1965, Eggen 1968, 1969, Greenstein 1969). The Greenstein (G-R) color

TABLE 1

THE ZZ CETI STARS

Star	α (1950)	δ	V	(B-V)	(U-B)	(G-R)	Ref.
BPM 30551	01 04.7	-46 26	15.42	+0.17	-0.50	-----	1, 2
ZZ Ceti	01 33.7	-11 36	14.10	+0.20	-0.54	-0.43	3
BPM 31594	03 41.8	-45 58	15.03	+0.21	-0.66	-----	4
HL Tau-76	04 16.8	+27 13	15.20	+0.20	-0.50	-0.39	5
G38-29	04 17.0	+36 09	15.63	+0.16	-0.53	-0.42	6
G191-16	04 55.4	+55 21	15.98	+0.03:	-----	-0.44	7
GD 99	08 58.7	+36 19	14.55	+0.19	-0.59	-----	8
G117-B15A	09 21.2	+35 30	15.52	+0.20	-0.56	-0.45	8, 9
GD 154	13 07.6	+35 26	15.33	+0.18	-0.59	-0.43	10
L19-2	14 25.4	-81 07	13.75	+0.25	-0.53	-----	2, 11
R808	15 59.5	+36 57	14.36	+0.17	-0.56	-0.38	8
G226-29	16 47.6	+59 09	12.24	+0.16	-0.62	-0.43	12
G207-9	18 55.7	+33 53	14.64	+0.17	-0.60	-----	13
G185-32	19 35.2	+27 36	13.00	+0.17	-0.57	-0.42	7
GD 385	19 50.4	+25 02	15.13	+0.19	-0.68	-0.43	14
GD 556	23 11.8	+55 12	16.21	-----	-----	-0.38	7
G29-38	23 26.3	+04 58	13.10	+0.20	-0.65	-0.43	15

1) Hesser et al. (1976)
2) McGraw (1977)
3) Lasker and Hesser (1971)
4) McGraw (1976)
5) Landolt (1968)
6) McGraw and Robinson (1975)
7) McGraw et al. (1980)
8) McGraw and Robinson (1976)
9) Richer and Ulrych (1974)
10) Robinson et al. (1978)
11) Hesser et al. (1977)
12) Fontaine et al. (1980)
13) Robinson and McGraw (1976)
14) Fontaine et al. (1981)
15) Schulov and Kopatskaya (1973)

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index (Greenstein 1976) derived from multichannel-scanner observations and references to the discovery of photometric variability in each star are also included. These references contain the history of the ZZ Ceti stars. As discoveries of new variables occurred and new characteristics of their variability became apparent, the authors of the discovery papers advanced various suggestions concerning the nature of the ZZ Ceti phenomenon. These suggestions have been tested and refined to produce the current understanding of ZZ Ceti stars.

Table 1 lists a very homogeneous set of variable stars -- all have DA spectral type and all have colors in the range + 0.15 to + 0.25, while colors for DA dwarfs can range from (B-V) < - 0.2 for hot stars to (B-V) > 0.6 for the coolest recognizable DA dwarfs. The (B-V) color range given here is narrower than previously reported (e.g. Robinson 1979) because of a new measurement of (B-V) = 0.17 $\pm$ 0.04 for BPM 30551 (Wegner 1980). This value is used in place of (B-V) = 0.29 (Eggen 1969) which made this star the reddest variable by Δ(B-V) = 0.04. The use of this value forces a readjustment of the satistics of ZZ Ceti stars and nonvariables with colors in the appropriate range. The faint variable G191-16 has an estimated (B-V) = 0.03 derived from multichannel-scanner observations (Greenstein 1974). Because of the more recent revised (G-R) color which is totally consistent with (G-R) values for the other stars listed in Table 1, we feel the reported (B-V) value to be inaccurate and we neglect it here.

DA spectral type and (B-V) colors near + 0.20 were the criteria used by most of the surveys for the selection of candidate stars for variability. These criteria were well tested, however, by numerous observations of non-DA stars and white dwarfs distributed over a wide color range. Figure 1 shows the (U-B) - (B-V) two-color diagram of 125 white dwarfs investigated for variability. The 15 ZZ Ceti stars for which colors are available are plotted as filled triangles. Non-variable DA dwarfs are plotted as open circles; the helium-rich DB dwarfs, metallic line DF dwarfs, carbon-rich C_2 and λ4671 dwarfs and hot DO dwarfs are represented by the symbols B, F, 2, λ and Ø, respectively. White dwarfs of unknown spectral type are designated by U. Typical uncertainties are shown. The solid line is the locus of the DA sequence for log g = 8 (Terashita and Matsushima 1969). Colors for models at 7, 8, 12, 15, 20 and 25 x 10^3 K are plotted as crosses.

A compilation of all published null results of surveys for variability has been produced by Hesser, Lasker and Neupert (1979). Two notes on this compilation (their Table 2) are in order. The first is that they list as variable two stars which are not single white dwarfs. These are HZ29 and G61-29, both of which are close binary helium mass transfer systems. A third star listed as variable, the DC dwarf G44-32, has been discussed as constant by Robinson (1980). The second note is that two stars listed as apparently constant, G226-29 and G185-32, are ZZ Ceti variables. The possibility certainly exists that other stars in this list are also variable.

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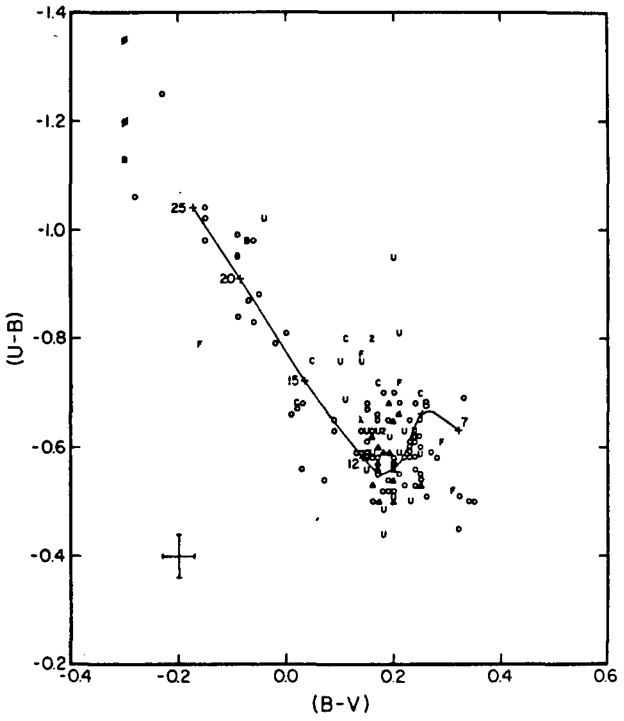

Figure 1. The Johnson two-color diagram of white dwarfs investigated for variability.

Because a large number of white dwarfs including all spectral types and a broad range of color have been investigated for variability and found constant in the period range from about 20s to 2000s, we are confident that the ZZ Ceti stars have been uniquely defined as DA white dwarfs with (B-V) colors near + 0.20. ZZ Ceti variability is an isolated, distinct phenomenon among white dwarfs, in general.

The close grouping of colors of the ZZ Ceti stars in Figure 1 clearly indicates that the luminosity variations are caused by an intrinsic mechanism in DA dwarfs. The presence of hydrogen in the atmosphere of a white dwarf is a physical prerequisite for variability. In the range of color populated by the ZZ Ceti stars, (B-V) is primarily a temperature indicator. Thus, we are driven to the conclusion that ZZ Ceti variability arises from an intrinsic mechanism which is temperature sensitive and depends upon the structure of the white dwarf atmosphere and envelope -- that is, a pulsation mechanism.

McGraw (1979) used Strömgren colors to better define the physical properties of the ZZ Ceti stars. The instability zone found in this investigation has a "blue edge" at about 13,500 K and a "red edge" at

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about 10,500 K on the DA cooling sequence. The mean surface gravity derived for the ZZ Ceti stars is about log g $\sim$ 8 -- a value entirely consistent with nonvariable DA stars. The observed temperature range corresponds to the maximum hydrogen opacity at log g = 8. Greenstein (1979) has obtained multichannel and SIT spectra of several ZZ Ceti variables and has concluded that they are normal DA white dwarfs. Liller and Hesser (1980) have examined the historical records of 12 ZZ Ceti stars and two other white dwarfs in the Harvard plate collection. They find no evidence of other types of variability on long timescales. All of the available observational data indicate that the ZZ Ceti stars are single, normal DA white dwarfs.

Because ZZ Ceti stars are normal DA white dwarfs, variability must be considered an evolutionary effect. That is, as a DA star cools, it follows an evolutionary track very nearly parallel to a line of constant gravity in, for example, the two-color diagram of Figure 1. All DA stars will eventually pass through the temperature range in which the variables occur.

Current research by Fontaine and McGraw has been aimed at defining the fraction of DA stars which pulsate as they cool through the instability range. If the (B-V) color is used to define the temperature domain of the ZZ Cetis, one finds that about 25% of the DA stars with (B-V) colors in the appropriate range are variable (Robinson 1979). The implication is that the "correct" temperature by itself is a necessary, but <u>not</u> sufficient, criterion for a DA star to become pulsationally unstable. To correctly predict which DA stars become unstable would involve specifying some unobservable parameter, such as the run of chemical composition through the atmosphere or envelope. If, however, the (G-R) color derived by Greenstein (1976) from multichannel scanner observations is used as the temperature discriminant, the fraction of variables in the "correct" temperature range becomes very much higher. This is demonstrated by a series of histograms prepared by Fontaine (1980) and shown in Figure 2. The top panel shows the distribution in color of 97 DA stars with available Johnson colors which have been searched for variability. The hatched area represents the contribution of variables. As stated, about 25% of the stars in the color range $0.16 \leq (B-V) \leq 0.25$ are variables. The middle panel shows the distribution of DA stars with (G-R) colors which have been searched for variability. In this histogram <u>all</u> of the stars in the range $-0.45 \leq (G-R) \leq -0.38$ are variables. A temperature scale derived from Shipman's (1979) calibration of Greenstein's colors is indicated above the region of variability. The derived temperature range for the variables is about $11,000 \text{ K} \leq T_e \leq 13,000 \text{ K}$. Finally, the bottom panel shows the stars in the middle panel distributed by their (B-V) colors. It is clear that the (G-R) color is a better discriminant of variability than is the (B-V) color. There are two reasons for this. The first is that the G and R bandpasses are specifically chosen to be astrophysically meaningful for white dwarfs whereas the B and V bandpasses were not. Also, the (G-R) colors are much more homogeneous and photometrically accurate than (B-V) colors

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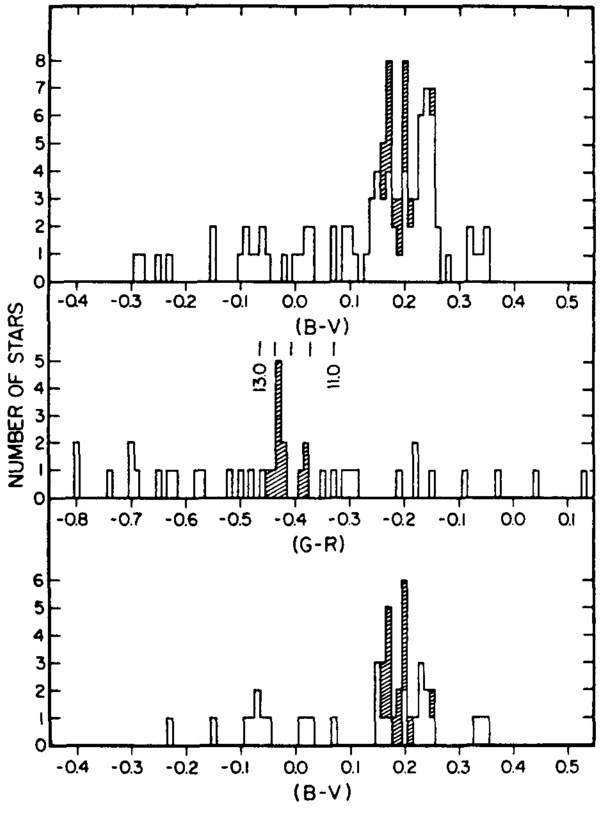

Figure 2. The distribution of DA stars with respect to (B-V) and (G-R) colors. In each panel the contribution due to ZZ Ceti stars is hatched. Above the (G-R) distribution is a temperature scale due to Shipman (1979) ranging from 11.0 x 10^3 K to 13.0 x 10^3 K, with tick marks every 500 K.

because they were obtained on the same telescope with the same instrument covering a wider range in wavelength, thus allowing more accurate reduction of the data. The (G-R) index is designed to be primarily a temperature indicator in the color range of the ZZ Ceti stars. Because all of the stars in the ZZ Ceti range of colors are variable, independent of gravity or composition as measured by Greenstein colors, we feel that temperature and temperature alone is, in fact the parameter being measured.

From this analysis, utilizing a more precise temperature indicator for white dwarfs, with lower observational uncertainties, we conclude that the vast majority, and possibly all, of the DA white dwarfs become pulsationally unstable as they evolve through the temperature range 13,000 K to 11,000 K (Fontaine et al. 1981). If the hypothesis that all

DA stars become ZZ Ceti variables is correct, it will have important consequences for the modeling of atmospheres and envelopes of DA dwarfs, in general. It will also impact the theoretical investigation of white dwarf pulsations.

III. THE PULSATIONAL PROPERTIES OF ZZ CETI STARS

Though the ZZ Ceti stars are physically very homogeneous, their light curves vary dramatically from star to star. Figure 3 shows segments of the light curves of three ZZ Ceti stars. The vertical axis is expressed as counts per second outside the atmosphere, and the horizontal axis represents time in units of hundreths of a day. The light curve of HL Tau-76 is representative of those variables with the largest amplitudes, that is, peak-to-peak amplitudes of 0.2 to larger than 0.3 mag.

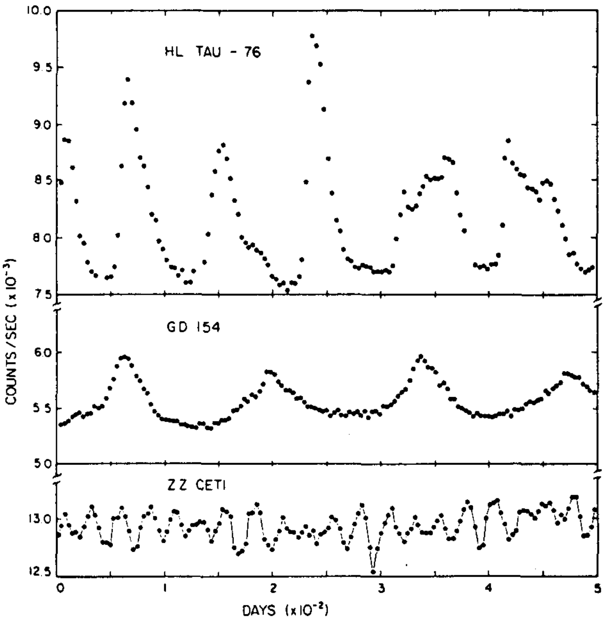

Figure 3. Typical light curves for ZZ Ceti variables.

The pulse shapes of these stars are distinctly nonsinusoidal, typically with a rapid rise to a sharp maximum followed by a somewhat slower decline. The arrival of the pulses is quasi-periodic at best, and the quasi-periods associated with the large amplitude variables tend to be longer than the mean for the ZZ Ceti stars -- typically 800 - 1000 s.

The intermediate amplitude variables, those with peak-to-peak variations of about 0.05 to 0.2 mag, are represented in Figure 3 by

GD 154. These variables tend to have somewhat more periodic pulse arrival times and the pulse shapes are less distorted than the large-amplitude variables. The quasi-periods of these variables also tend to be shorter, as well -- typically 300 to 800 s, though GD 154 itself is the exception to this, having the longest known primary period of any ZZ Ceti variable -- about 1186 s.

ZZ Ceti itself is a typical low-amplitude variable. These variables, all with amplitudes less than about 0.03 mag, tend to have nearly sinusoidal, multiply periodic light curves. The multiple periods often manifest themselves as "beats" in the light curves, some of which can be seen in the segment of the ZZ Ceti light curve in Figure 3. The periods of the low amplitude variables, which range from about 100 to 300 s, are exceedingly stable.

Stover et al. (1980) have analyzed all available high-speed photometry of ZZ Ceti, spanning about eight years, and have derived an upper limit of $|dP/dt| \equiv |\dot{P}| < 2 \times 10^3$ s/s. More recently, Kepler et al. (1981) have analyzed the period structure of the low-amplitude variable G117-B15A and have derived $|\dot{P}| < 6.5 \times 10^{-14}$ s/s for the largest amplitude of the six periods present in the light curve. These extremely low values of $\dot{P}$ are within two orders of magnitude of the rate of period change one would expect to see as a result of the cooling of the white dwarf. That is, as the white dwarf cools, its structure changes and this change is reflected in a changing period of the nonradial gravity-mode pulsations we believe responsible for the luminosity variations of the ZZ Ceti stars (cf. Robinson, this colloquium).

The strongest argument for the identification of the pulsations of ZZ Ceti stars as nonradial g-modes is the fact that the observed periods are more than two orders of magnitude too long to be identified with radial pulsations on a white dwarf. They much more closely match periods predicted for nonradial g^+ modes (Osaki and Hansen 1973). Without exception, the light curves of the ZZ Ceti stars are all multiperiodic. In each case, the period ratios are inconsistent with radial pulsation overtones, but can easily be explained in terms of nonradial modes.

The power spectrum representation of the light curves of ZZ Ceti stars has proven to be a useful tool in deciphering the period structure of these stars. Power at discrete frequencies in the power spectrum arises from two sources. The first is the frequencies of the independent pulsations modes, and the second arises from the pulse shapes themselves. Because all ZZ Ceti stars are multiperiodic, at least two peaks appear in the power spectra, even for the lowest amplitude variables. For larger amplitude variables, nonlinearity in the form of nonsinusoidal pulse shapes becomes important. In these cases the first, and occasionally the second and third harmonics of the primary pulsation frequencies occurs in the power spectrum. These components of the power spectrum relate only to the pulse shape as it is affected by nonlinearity. At larger amplitudes, coupling between modes may occur. In this case, peaks occur in the power spectrum at or near frequencies given by:

$f = mf_0 + nf_1$, where m and n are integers and f_0 and f_1 are frequencies of primary pulsation modes. Again, this is a manifestation of highly nonlinear pulsations. A third effect, rotational modulation of the nonradial pulsation, can also produce additional frequencies, equally space with respect to primary pulsation frequencies, with $\Delta f = \Delta m\Omega$, where Ω is the star's rotation frequency and Δm is the appropriate spacing in m (cf. McGraw 1980).

It is well-known that nonlinear effects ultimately limit the amplitude to which a pulsation may grow. Recently, Fontaine et al. (1980) observed a monotonic growth in amplitude of a pulsation mode in GD385. In eight observations spanning about 80 days, only the primary frequency and its first harmonic were present in the power spectrum. In the ninth observation, obtained three days later, the power spectrum had changed dramatically, with the appearance of multiple peaks, all of which had amplitudes at least an order of magnitude lower than the primary peak on the last night it was observed. This lead to the hypothesis that the increase in amplitude prior to the change represented the growth of a single pulsation mode with a growth rate of about 10^{-6} and that the mode was finally limited by nonlinear coupling to additional pulsation modes. If further observational and theoretical work bears out this hypothesis, it represents the first measurement of the complex eigenfrequency of a pulsation mode in a real star.

It is clear that in the ZZ Ceti stars we observe all of the phenomena associated with pulsating stars, and nonradially pulsating stars in particular. These effects are well-defined because we can observe many pulsations of a ZZ Ceti star per night. This ensures that we sample all of the mechanisms at work in the star. Because observers have been able to accurately define the pulsation properties of the ZZ Cetis, they have been very effective in suggesting the course of theoretical investigations of these stars.

A theoretical investigation by Dziembowski (1979) has found unstable g-modes of low order with periods approximating those observed in ZZ Ceti stars. The model he used, however, is not particularly realistic with respect to DA white dwarfs and the driving comes from a deep region in this model. From his theoretical review of nonradial pulsations and the model calculations, Dziembowski concludes that the variability of ZZ Ceti stars is caused by g-mode pulsations driven by an opacity mechanism and that rotational splitting of these pulsations does occur -- all of which agrees in detail with observations.

More recently, Winget et al. (1981) have investigated g-mode pulsations in realistic, evolved, layered DA models. They find that "trapped modes" with periods closely matching those of ZZ Cetis occur due to a resonance between the mode's radial wavelength and the thickness of the hydrogen layer. Continuing work along these highly promising lines will decide which of those modes are unstable. Again, the significance of the hydrogen layer to the pulsational properties of ZZ Ceti stars has been pointed out by observers (cf. Robinson 1979).

At this time, the exchange between pulsation theorists and observers promises to give a reasonably detailed understanding of the pulsations of ZZ Ceti stars. Certainly portions of this understanding will be applicable to other pulsating stars, as well.

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DISCUSSION

SIMON: I don't understand the result with (G - R) as compared to (B - V). What is the physical difference in the atmosphere?

McGRAW: There is no physical difference in the atmosphere. Remember that (G - R) is basically a temperature index, as is (B - V). As a DA star evolves into the correct temperature region, it becomes variable.

SIMON: Is the idea then that (G - R) defines a narrower region?

McGRAW: The temperature bandpass from Harry Shipman's models turns out to be 1,000-13,000K. That is the same, within observational uncertainties as we derived earlier.

SIMON: At the (B - V) in that range, there were nonpulsating stars. To the theoretician, a temperature is a temperature.

McGRAW: That is correct. When you measure a color with a filter system, you end up with observational uncertainties that are a few hundredths of a magnitude. That means that we have a strip which is a few hundredths of a magnitude wide, and so a star on either side of it has a probability of having a measured (B - V) which actually falls inside of that strip. What I am saying is that (B - V) colors do not discriminate as well. The observational uncertainty is what is leading to the scatter.

J. COX: I think that the growth rate reported for GD385 is very exciting. To an order of magnitude, it seems to be about right.