THE WILSON-BAPPU MAGNITUDE–LUMINOSITY RELATION: A RETROSPECTIVE[1]

Jeffrey L. Linsky

JILA, University of Colorado and NIST

Campus Box 440, Boulder, CO 80309-0440.

Received ________________________; accepted ________________________

[1] This paper is a revision of an earlier review of this topic (Linsky 1980).

ABSTRACT

The correlation between the separation in wavelength of the Ca II K line emission features and the absolute visual magnitudes of late-type stars presented in the landmark 1957 paper by Wilson and Bappu provided a serious challenge to astronomers at the time and stimulated the development of a new field of research. Early interpretations floundered on the lack of a realistic physical model that could identify whether the emission features are formed in the Doppler core or the damping wings. With the development of "partial redistribution" formulation of the radiative transfer equation, the K_1 minimum features were recognized as being formed by nearly coherent scattering in the line wings. Ayres (1979) showed that the Wilson-Bappu effect is a natural consequence of the dependence of chromospheric thickness and electron density on gravity in a hydrostatic equilibrium atmosphere. Although there are some issues that still need to be addressed concerning how to compute line profiles in stellar atmospheres that have very low densities, are inhomogeneous with large mass motions, or contain strong magnetic fields, the Wilson-Bappu effect seen in the resonance lines of Ca II, Mg II, and other chromospheric lines is now understood on the basis of a physically self-consistent model.

Subject headings: radiative transfer—stars: chromospheres—stars: late-type—Wilson-Bappu effect

"It is important to realize that a chromosphere is a completely negligible part of a star. Neither its mass nor its own radiation makes a significant contribution to those quantities for the star as a whole. Moreover, I know of no essential role that a chromosphere fills in the life of a star. . . . Hence an outsider might be pardoned for asking why this many people have spent four days here studying something which seems as nonessential and insignificant as chromospheres."

Olin Wilson (1973)

1. INTRODUCTION

While Olin Wilson was a pioneering and insightful observational astronomer whose work was well-known and appreciated, he was very modest in describing his own work. The above quote, which I extracted from his summary paper presented at IAU Colloquium No. 19 on “Stellar Chromospheres” (Wilson 1973), shows a very modest description of the research field that he almost single-handedly created. This quote also hints at his impish delight in challenging those theoreticians who hastily “explained” the surprising relation between the measured widths of the Ca II H (3968 Å) and K (3933 Å) emission features and the stellar absolute visual luminosities published in his seminal paper with Vainu Bappu (Wilson & Bappu 1957, hereafter WB).

Olin was too modest. His pioneering paper stimulated dozens of attempts by leading theoreticians to explain the simple observational facts that he so clearly presented. Olin was also too modest in describing the role that chromospheres can play in stellar evolution: the same strong magnetic fields responsible for heating the chromospheric layers and thus producing the Ca II emission features also play a major role in the loss of angular momentum, coronal heating, and the acceleration of stellar winds. The study of Ca II emission continues to provide us with very useful empirical indicators of stellar age, rotation, dynamo activity, and stellar evolution.

2. THE WILSON–BAPPU EFFECT

Wilson and Bappu published the widths of emission features in the cores of the Ca II H and K lines for 185 stars of spectral types G, K, and M and all luminosity classes. These widths were measured using photographic spectra obtained with the Mt. Wilson 100-inch telescope. The emission line widths, W_0, are Wilson’s measurements of the wavelength displacement between the "outer edges of the Ca II emission lines," converted to a velocity width in km s^{-1}. The precise meaning of "outer edges" is unclear. The measurements in WB refer to a width located somewhere between the separation of the red ($\mathrm{K_{2R}}$) and blue ($\mathrm{K_{2B}}$) emission peaks (usually designated as $W(\mathrm{K_2})$), and the separation of the red ($\mathrm{K_{1R}}$) and blue ($\mathrm{K_{1B}}$) absorption minima (usually designated $W(\mathrm{K_1})$). These quantities are shown, for example, in Fig. 1 of Ayres (1979) and Fig. 1 of Scoville & Mena-Werth (1998).

WB were surprised to find that the logarithms of the emission line widths are linearly correlated with the stellar absolute visual magnitudes (M_v) over a 15 magnitude range in the latter. Perhaps even more surprising than the linear correlation and its validity over a very large range in luminosity is the absence of any dependence of W_0 on a star's spectral type, surface temperature, emission line strength, or metallicity. WB also showed that the Sun fits this width-luminosity relation (commonly called the Wilson-Bappu effect), an early step in the joint study of solar and stellar phenomena now called the "solar–stellar connection."

Soon after WB presented their simple correlation between Ca II K-line emission core widths and stellar luminosity, many astronomers expanded the data base and proposed explanations for the relation. Part of the fascination of this topic has been the inherent simplicity of the correlation and the prospect of obtaining valuable insights concerning stellar distances and chromospheric properties from simple measurements of line widths. Unfortunately, there are subtle issues — critical to the understanding of the Wilson-Bappu effect — that were not understood for more than a decade after the original paper was published.

Many authors arrived at relations similar in functional form to that originally proposed by WB on the basis of simple calculations not based on a realistic physical model for the formation of the Ca II emission lines. In order to infer the properties of a stellar atmosphere from the Ca II emission features with any credibility, however, one must use physically realistic radiative transfer calculations. In the next two sections I will briefly summarize the observational and theoretical work that identified the physical principles that underlie the Wilson-Bappu effect.

3. EMPIRICAL WIDTH–LUMINOSITY RELATIONS

The width that WB actually measured, W_0 (km s^{-1}), is the separation between the outer edges of the Ca II emission features on 10 Å mm^{-1} photographic spectrograms. Lutz (1970) showed that W_0 is very nearly equal to the full-width at half-maximum (FWHM) of the emission core. WB and Wilson (1959) proposed the following expression for the K-line width-luminosity relation,

$$M_v = 27.59 - 14.94 \log[W_0(\mathrm{K})], \tag{1}$$

where M_v is the absolute visual luminosity. Subsequent studies have redetermined this relation from different data sets. Recently, Wallerstein, Machado-Pelaez, & Gonzalez (1999) have determined a Ca II width-luminosity relation using *Hipparcos* parallaxes to derive the absolute stellar visual magnitudes. Their linear fit to the weighted data is

$$M_v = 28.83 - 15.82 \log[W_0(\mathrm{K})], \tag{2}$$

which is not very different from Eq. (1). Like WB, they also find no dependence on emission strength or spectral type, except that G supergiants tend to have larger widths than predicted by Eq. (2).

Width-luminosity relations have now been found for several other chromospheric emission lines, for example, the analogous Mg II h (2803 Å) and k (2796 Å) resonance lines, Lα, and Hα. The first large compilation of Mg II k-line widths is that of Weiler & Oegerly

(1979), based on *Copernicus* observations of 49 late-type stars. Their expression,

$$M_v = 34.93 - 15.15 \log[W_0(\mathrm{k})] \tag{3}$$

has essentially the same slope as that for Ca II, even though the Mg II widths were measured at the base of the emission feature. Scoville & Mena-Werth (1998) analyzed IUE spectra of the Mg II lines of 94 late-type stars, obtaining correlations of the absolute magnitude with the base width (W_{base}), peak width (W_{peak}), and FWHM (W_{FWHM}) of the Mg II k line. They find, for example, that

$$M_v = 38.20 - 16.31 \log[W_{base}(\mathrm{k})]. \tag{4}$$

A study of Mg II h and k line widths in M dwarfs by Elgaroy, Engvold, & Carlsson (1990), however, showed that a number of these stars with M_v fainter than +8 have widths narrower than predicted by the WB relation.

Using a small sample of Lα widths (actually the FWHM of the emission line), McClintock *et al.* (1975) obtained the relation

$$M_v = (40.2 \pm 4.5) - (14.7 \pm 1.6) \log[W_0(\mathrm{L}\alpha)]. \tag{5}$$

Kraft *et al.* (1964), LoPresto (1971), and Fosbury (1973) studied the dependence of the Hα line half-width, defined in several different ways, on M_v, but they did not propose functional relationships like those in Eqs. (1) to (5).

Different characteristic features in the K line also show width-luminosity relations. For example, Ayres *et al.* (1975) and Engvold & Rygh (1978) found that the separations of the K_1 minimum features are correlated with M_v. Based on high resolution spectra of 26 late-type stars, they derived

$$M_v \approx const. - 15.2 \log[W(\mathrm{K}_1)]. \tag{6}$$

Lutz, Furenlid, & Lutz (1973) found that the entire damping wings of the K and K lines broaden with increasing stellar luminosity. Based on a sample of 32 stars observed with high dispersion, Cram *et al.* (1979) reported that both the K_2 peak separation and the K_1 minimum separation exhibit essentially the same width-luminosity slope as the FWHM.

4. PHYSICAL INTERPRETATIONS OF THE WIDTH–LUMINOSITY RELATIONS

The agreement among the slopes of the six relations cited above indicates a common, presumably simple, origin for the various line widths. As a first step toward understanding that origin, several authors have expressed the line widths empirically in terms of fundamental stellar parameters (gravity, effective temperature, and metal abundance). For example, Lutz & Pagel (1982) proposed the relation

$$\log W_0 = -0.22 \log g + 1.65 \log T_{eff} + 0.10[Fe/H] - 3.69, \tag{7}$$

based on observations of 55 stars. I should mention here that WB first suggested the possibility that W_0 might depend on metallicity and said that "this possibility must be kept in mind." Lutz & Pagel argued that their relation is more accurate than those derived previously without an abundance term, although the metallicity correction is small except for Pop II stars. For the K_1 width, Cram *et al.* (1979) found that

$$\log W(\mathrm{K}_1) = -(0.20 \pm 0.02) \log g + (1.1 \pm 0.2) \log T_{eff} - 3.76, \tag{8}$$

and Engvold & Rygh derived a coefficient of –0.16 for the first term.

To proceed further one must have a realistic physical model for the formation of the emission features in the cores of the Ca II lines. WB recognized this point when they said, "It is clear that the first point to be considered concerns the means by which the Ca II emission lines are broadened. There are only two possibilities: either the widths are a manifestation of Doppler effect, i.e., motions, presumably of a turbulent nature, or they are due to abundance broadening as a result of large optical thickness."

4.1. Doppler Core Approximation

WB and many subsequent authors assumed that the width of the Ca II K line emission feature, generally taken to be W_0, is formed in the Doppler core of the line profile and therefore responds mainly to turbulent velocities in the chromosphere. WB argued that W_0 measured a portion of the emission line that is optically thin, in which case the inferred turbulent velocity is more than twice the sound speed in the Sun and 20 times the sound speed in supergiants. Such highly supersonic motions are readily damped and thus unlikely. Hoyle and Wilson (1958) argued that these high velocities are hydromagnetic waves. Goldberg (1957) showed, however, that the Doppler cores of the Ca II lines are very optically thick (which is indeed the case for late-type stars), thereby decreasing the inferred turbulent velocities by a factor of 3–4. Large optical depths are consistent with the H and K line widths being about equal.

Scharmer (1976) followed Goldberg (1957) in assuming that $W_0 \approx 6\overline{u}$, where $\overline{u}$ is the mean chromospheric turbulent velocity. The factor of 6 comes from W_0 being the full (not half) width and the edge of the Doppler core being 3 half-widths from line center, where a Doppler profile has $e^{-9} = 1.2 \times 10^{-4}$ times the opacity at line center. Sharmer arrived at the inevitable result that such velocities are supersonic in giants and highly supersonic in supergiants. Using conservation equations and taking the mechanical energy flux proportional to $\overline{u}^3$, Scharmer showed that $W_0 \approx 6\overline{u} \sim g^{-1/4}$ in agreement with the empirical relation, Eq. (7). However, the derived value of $\overline{u}$ for the Sun is 22 km s^{-1}, which is far larger than any sensible estimate of turbulent velocities in the solar chromosphere.

Fosbury (1973) studied the Ca II and Hα widths together in order to better determine chromospheric turbulent velocities. He estimated chromospheric wave fluxes from the line widths and concluded that the amplitude of upward propagating acoustic waves increases with stellar luminosity. Lutz & Pagel (1982) then derived a relation similar to Eq. (7) assuming slab geometry with a geometrical thickness equal to the K-line thermalization length, complete frequency redistribution (CRD), and Doppler control of W_0.

These papers and previous studies of the same type can reproduce some empirical properties of the Wilson-Bappu effect such as the gravity dependence, but these studies have a number of major difficulties. (1) They assume that W_0 is located in the Doppler core, but give no theoretical or empirical justification for this assumption. (2) They either ignore radiative transfer altogether, or treat line transfer in a wholly unrealistic manner. (3) They typically do not compute chromospheric densities and ionization self-consistently. (4) They do not attempt to explain high resolution solar observations or measured turbulent velocities in the solar chromosphere. We shall see that those studies which solve the radiative transfer equation including the essential physics of spectral line formation of optically thick resonance lines will do a far better job of predicting the empirical properties of the Wilson-Bappu effect.

4.2. Damping Wing Approximation

The alternative physical interpretation for the width-luminosity relations assumes that the width between the K_1 features, $W(K_1)$, is formed in the damping wings of the line profile. Inside the Doppler core (within about 3 Doppler halfwidths, $\Delta\lambda_D$, of line center) of a resonance line like the Ca II H and K lines, thermal motions of atoms are sufficient to redistribute in frequency all scattered line photons. Thus the line photons lose memory of the wavelength at which they were created or last scattered and the complete redistribution

(CRD) approximation for the transfer equation is sensible for the Doppler core. For the wings of resonance lines outside of the Doppler core, photons are scattered nearly coherently in the atom's rest frame and thermal motions of atoms in the observer's frame of reference are insufficient to scatter photons back into the line core. Thus the radiative transfer equation must accurately describe the complete frequency redistribution of scattered line photons in the line core and nearly coherent scattering in the line wings. This approach called partial redistribution (PRD) was applied to optically thick chromospheric resonance lines in a series of seven papers entitled "Resonance line transfer with partial redistribution" beginning with Milkey & Mihalas (1973). Important papers describing the formation of the Ca II resonance lines by include Milkey, Shine, & Mihalas (1975), Shine *et al.* (1975), and Uitenbroeck (1990a, 1990b). In general, the cores of the Ca II lines computed with the CRD and PRD formulations have a similar shape, although the K_3 feature is darker in PRD calculations. The big differences between line profiles computed with the two different approaches are that the K_2 peak computed in PRD is less bright and limb darkens compared to CRD calculations that show strong limb brightening, and the K_1 features computed with PRD lie much closer to line center and limb darken whereas in CRD they limb brighten. Thus any realistic analysis of the damping wings of the Ca II and Mg II resonance lines requires PRD radiative transfer calculations.

The widths of line features formed in the damping wing are sensitive primarily to the mass column density above the temperature minimum and are relatively insensitive to chromospheric turbulent velocities. Engvold & Rygh (1978) showed empirically that the full width $W(\mathrm{K}_1) \approx (7.8 \pm 1.7)\Delta\lambda_D$, and a Gaussian line profile at $\Delta\lambda = 3.9\Delta\lambda_D$ has negligible opacity ($e^{-(3.9)^2} = 2 \times 10^{-7}$). Thus the K_1 minimum features must be formed in the damping wings of the line profile. With the approximation that the K_1 feature is formed at the temperature minimum (but see §4.3), which empirical models suggest occurs at roughly the same continuum optical depth in late-type stars, Ayres, Linsky, & Shine

(1975) used the P^2 dependence of H^- opacity to derive

$$\log W(\mathrm{K}_1) = -0.25 \log g + 0.25 \log A_{met} + const. \tag{9}$$

The coefficient of the $\log g$ term is similar to the coefficient for the empirically derived gravity dependence in Eqs. (7) and (8). Thomas (1973) proposed an alternative explanation in which the location of the base of the chromosphere, which determines $W(\mathrm{K}_1)$, may depend on the upward mass flux, which in turn is related to the chromospheric heating rate.

Clearly a synthesis is needed to determine whether or not these very different explanations for W_0 and $W(\mathrm{K}_1)$ are related, and which, if either, is consistent with a realistic study of spectral line formation in the K line. An important paper by Ayres (1979) goes a long way in addressing these critical questions. Ayres derived simple scaling laws for the thickness and mean electron density of stellar chromospheres as functions of surface gravity and nonradiative heating rate, assuming that the lower chromosphere is in hydrostatic equilibrium and that the nonradiative heating rate is relatively constant per gram of material throughout the 10 scale-height thick chromosphere. He also took into account the influence of ionization on the general structure of the chromosphere and on the radiative cooling functions. His partial redistribution (PRD) radiative transfer calculations showed that the K_1 features are formed in the damping wings of the line profile. His calculations were also able to match the observed limb darkening of the solar Ca II features (Shine *et al.* 1975; Zirker 1968), which provides strong evidence for near coherent scattering (and thus little Doppler redistribution) at the base of the chromosphere where the photons observed outside of the emission peaks are formed. Ayres derived the theoretical relation

$$\log W(\mathrm{K}_1) = -1/4 \log g + (7/4 \pm 1/2) \log T_{eff} + 1/4 \log \mathcal{F} + 1/4 \log A_{met} + const, \tag{10}$$

where $\mathcal{F}$ is a scaled nonradiative heating rate that measures stellar "activity" and A_{met} is the metal abundance. The coefficients are similar to those in the empirical relation [Eq.

(8)], and the predicted width ratio $W(\mathrm{k}_1)/W(\mathrm{K}_1) \approx 2.5$ is consistent with the empirical stellar value of 2.5 ± 0.3 estimated by Ayres *et al.* (1975) and the solar value ≈ 2.3.

Ayres (1979) concluded that the K_2 emission peaks are formed just outside of the Doppler core and assumed that the line source function is a maximum at one thermalization length below the top of the chromosphere. This approximation led to

$$\log W(\mathrm{K}_2) = -1/4 \log g - (5/4 \pm 1/2) \log T_{eff} - 1/4 \log \mathcal{F} - 1/4 \log A_{met} + 1/2 \log \xi + const, \tag{11}$$

where ξ is the turbulent broadening velocity. The ratio of the Mg II and Ca II emission peak separation based on the above relation is $W(\mathrm{k}_2)/W(\mathrm{K}_2) \approx 0.9$.

Several important conclusions can be drawn from this work.

(1) Both $W(\mathrm{K}_2)$ and $W(\mathrm{K}_1)$ scale as $g^{-1/4}$ if the total nonradiative heating rate does not vary greatly with gravity. The proportionality of $W(\mathrm{K}_2)$ to $g^{-1/4}$ follows from the dependence of the chromospheric electron density on gravity, while the proportionality of $W(\mathrm{K}_1)$ to $g^{-1/4}$ follows from the dependence of chromospheric thickness (e.g., mass column density) on gravity. The hydrodynamic models of Cheng, Engvold, & Elgaroy (1997) confirm the role that the chromospheric mass column density plays in determining W_0, although the turbulence term becomes important for the M dwarf stars which have very narrow Ca II and Mg II widths (cf. Elgaroy *et al.* (1990)). Because both $W(\mathrm{K}_2)$ and $W(\mathrm{K}_1)$ scale with gravity in the same way, it is reasonable to conclude that every measure of line width between K_1 and K_2, in particular W_0, should also scale the same way. The theoretical gravity dependence is also consistent with the Lutz–Pagel empirical scaling law $W_0 \sim g^{-0.22}$, and the other empirical width–luminosity relations (e.g., Cram *et al.* 1979).

(2) Ayres (1979) found that $W(\mathrm{K}_2) \sim \xi^{1/2}$ not $\sim \xi^1$ as was previously assumed. This results from the K_2 feature lying just outside of the Doppler core, in the Lorentzian

damping wings. This is consistent with the observation that the Ca II emission peaks limb-darken (Zirker 1968), which suggests significant coherent scattering, and thus little Doppler redistribution, where K_2 is formed. An important difference between the CRD and PRD calculations of the Ca II K line is that both the K_2 and K_1 features limb darken when the coherent nature of the scattering in the atom's reference frame is properly included in the calculation, whereas both features limb brighten in CRD calculations that ignore coherent scattering (cf. Uitenbroeck 1990a, 1990b). Engvold & Rygh (1978) found that on the average $W(\mathrm{K}_2)/\Delta\lambda_D = 6.8 \pm 0.4$ for their sample of 26 stars, which supports Ayres' assumption that K_2 is formed just outside of the Doppler core. Consequently, the $W(\mathrm{K}_2)$ and W_0 width-luminosity relations can be explained simply as a gravity effect without having to invoke highly supersonic turbulence in stellar chromospheres.

(3) Ayres predicted that $W(\mathrm{K}_2)$ should decrease with increasing $\mathcal{F}$ (i.e., increasing activity), while $W(\mathrm{K}_1)$ should increase with increasing $\mathcal{F}$. A good confirmation of these predicted opposite dependencies on the nonradiative heating rate is found by comparing solar plage profiles of Ca II (e.g., Shine & Linsky 1972) with those of the mean quiet Sun. In particular, the enhancement of the nonradiative heating rate is large and easily estimated in plages, which have the same effective temperature, gravity, and other stellar parameters as the quiet Sun. The Ca II plage observations and corresponding data for the Mg II k line are consistent with the $\mathcal{F}$ dependence of the $W(\mathrm{K}_2)$ and $W(\mathrm{K}_1)$ scaling laws. In addition, the K-line FWHM (which is approximately equal to W_0) appears to be independent of $\mathcal{F}$, which is accord with Wilson's (1966) result that W_0 appears to be independent of the strength of the emission feature. Linsky *et al.* (1979) did find rough agreement between measured K_1 widths of a large sample of stars and the gravity and chromospheric heating rate dependences given in Eq. (10), but Glebocki & Stawikowski (1978) found a weak dependence of W_0 on visually estimated line strengths, at least for very active stars.

4.3. The Importance of Noncoherent Scattering

Finally, I describe the calculations of Basri (1979), which cast the interpretation of width-luminosity relations in a new light. Basri made a number of prototype PRD calculations of line profiles for chromospheric models of late-type supergiants. His goal was to determine the factors involved in the formation of the emission widths of self-reversed chromospheric resonance lines under conditions of extreme coherency in the line wings. The PRD effects were expected to be particularly severe in supergiants owing to the very small collisional redistribution rates in the low densitiy envelopes of such stars.

As shown in Fig. 4 in Linsky (1980), Basri found that the emergent line profile in an isothermal atmosphere can have a self-reversed character for small values of the incoherence fraction Λ and r_0, the ratio of continuum to line center opacity, even though the atmosphere is isothermal and therefore has no temperature inversion. The origin of this isothermal K_1 minimum feature is as follows: Outside of the Doppler core the scattering of photons becomes more coherent with increasing $\Delta x = \Delta\lambda/\Delta\lambda_D$. As a result, the monochromatic source functions, $S_{\Delta x}$, rapidly decouple from the line center source function, $S_{LC} \approx B_\nu[T(\tau_0 \approx 1)]$, such that the emergent intensity decreases with increasing Δx. The intensity then rises in the far wings as $S_{\Delta x}$ begins to include a significant contribution from the assumed purely thermal background continuum. The extent to which this noncoherent scattering K_1 feature occurs depends on the relative importance of the competing terms. Increasing coherence (decreasing Λ) tends to emphasize this process (Mihalas 1970), while increasing collisional redistribution (increasing Λ) or increasing continuum absorption (increasing r_0) deemphasizes it. In addition, Doppler drifting — the frequency diffusion of photons in the observer's frame with each coherent scattering in the atom's frame owing to Doppler motions — tends to increase the probability of core photons wandering into the line wings. The redistribution of core photons increases the effective noncoherent scattering term, which in turn raises the K_1 minimum flux over the pure scattering case. In fact, Basri found that microturbulence can influence the location of the K_1 feature even though K_1 is formed far from the Doppler core, by enhancing the Doppler drifting mechanism. Basri's calculations demonstrate the critical importance of properly treating redistribution for very coherent cases and the potential dangers of naively assuming that the K_1 minimum feature is formed at the temperature minimum in extremely low gravity stars.

The prototype supergiant calculations leave us with the following unexpected results: (1) The k_1 and K_1 features of the Mg II and Ca II lines may not be formed at the temperature minimum in very low density chromospheres. (2) Neither the turbulent velocity nor the mass column density explanation for the $W(\mathrm{K}_1)$ vs M_v relation is viable by itself for low gravity stars. (3) Microturbulent velocities can play an important role in determining the values of $W(\mathrm{k}_1)$ and $W(\mathrm{K}_1)$ via the Doppler drifting mechanism. Even though these calculations refer to the arguably extreme case of very low density supergiant chromospheres, the most important message is that it is essential to simulate the line formation problem properly before one can make meaningful statements concerning the physical basis of width-luminosity relations.

Thus, while the theoretical explanation of the Wilson-Bappu effect is probably understood in broad outline, some details of the problem such as redistribution in very low density atmospheres, the role of atmospheric inhomogeneity and dynamics that are oversimply approximated by "turbulence", and the possible roles of magnetic fields in line formation remain to be studied in detail.

5. LOOKING BACK ON THE WILSON–BAPPU EFFECT

More than forty years ago the astronomical community was intrigued and puzzled by the curious relation between Ca II emission line widths and the absolute visual luminosity of late-type stars. WB first raised the question that intrigued many of the leading astrophysicists of the day when they said, "One might then ask: How can it be that a phenomenon taking place in the outer fringe region of a star is governed not by the local conditions but the total rate of energy generation deep inside? This is indeed a puzzling question. . . ." And so it was. Goldberg (1957) put it succinctly when he said, "Wilson's discovery presents astrophysicists with one of its most challenging and puzzling problems." The very practical use of the Wilson-Bappu effect as a simple tool for measuring the distances to late-type stars was also exciting at the time, long before *Hipparcos*, when trigonometric parallaxes did not have high accuracy. For the next decade the Wilson–Bappu effect was treated as a somewhat mysterious enigma – a phenomenon without a generally accepted explanation. The breakthrough in our understanding came in the 1970's when nearly coherent scattering in the line wings was properly included in the PRD formulation of the radiative transfer equation. When PRD was applied to chromospheric resonance lines, the Wilson-Bappu effect could be simply explained as a consequence of the increase in chromosphere thickness with decreasing gravity in a hydrostatic equilibrium atmosphere, except perhaps for the most luminous stars.

What are the long term consequences of the mysterious discovery presented by WB? In my opinion, the main consequience was the intellectual stimulus that it gave to the study of the outer atmospheres of stars where convective and magnetic energy are converted to heat, nonthermal particles, and a broad range of phenomena commonly called "stellar activity." In 1957 the presence of stellar coronae, winds, flares, magnetic fields, surface structure, x-ray emission, nonthermal radio emission, and ultraviolet emission lines were either speculation or just beginning to be studied. The connection between solar phenomena and phenomena on late-type stars now called the "solar-stellar connection" was then in its infancy. The excitement of the WB discovery probably encouraged Olin Wilson to begin a program of systematic long-term monitoring of the variability of the Ca II emission strength in late-type stars. This new program led to the discovery of stellar activity cycles, stellar magnetic dynamo properties, and a new technique for measuring stellar rotation rates. This important work is continuing at Mt. Wilson and elsewhere. For a summary of this work see, for example, Baliunas *et al.* (1995). The excitement generated by Wilson's work also encouraged others to observe stars at X-ray, ultraviolet, optical, and radio wavelengths with new generations of telescopes in space and on the ground. Thus the major legacies of the WB paper and Wilson's chromospheric monitoring program are the new fields of astrophysical research, "stellar activity" and the "solar-stellar connection."

This work is supported by NASA Grant S-56500-D to the National Institute of Standards and Technology. I thank Dr. Tom Ayres and Dr. Sallie Baliunas for their important comments on this paper.

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