Why are G-Band Bright Points Bright?

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Abstract. Magnetic elements in the solar atmosphere are most con-
spicuously visible in high resolution G-band filtergrams. In this paper
we show that the enhanced contrast in the G-band, as compared to the
continuum, is due to a depletion of CH in the deep photospheric layers
of the flux tube, where it is hotter than in the surrounding atmosphere
at equal optical depth, which increases the rate of collisional dissociation
of CH. As a consequence, the CH-lines weaken, allowing the continuum
more easily to "shine" through the forest of G-band CH-lines. We suggest
that other molecular bands may exhibit a similar behavior.

1. Introduction

The G-band is a molecular bandhead in the solar spectrum at around 430±1 nm,
consisting of electronic transitions between rotational and vibrational sublevels
of the molecule CH. The bandhead contains many blends of other species like
Fe, Ti, Ni, Cr, Ca, etc. At low spectral resolution the bandhead resembles a
single spectral line to which Fraunhofer (1814) assigned the letter "G".

The G-band of the solar spectrum was already in the center of interests of
Pecker & Peyturaux in 1948 when they showed that the center to limb variation
of the G-band relative to the continuum brightness passes through a maximum.
Pecker (1949) asserted this behavior to the effect of a "rough" solar surface
(see also Pecker 1999). More recently, G-band filtergrams of the solar surface
attracted the attention of solar physicists. If obtained at a high enough spatial
resolution, these images show brilliant bright points that are a manifestation of
small scale magnetic flux concentrations, so called, magnetic elements.

Muller & Roudier (1984) and Muller (1985) were the first to use a G-band-
pass filter to observe these tiny bright structures that later became known as
"G-band bright points". They often have an elongated shape, sometimes as-
sembled in a string, which resembles a short thread or crinkle at slightly lower
resolution. Time series of G-band filtergrams were obtained under exceptional
seeing conditions at the Swedish vacuum tower telescope on La Palma by Berger
band bright points can be taken as good proxies for magnetic elements. Sigwarth
et al. (2000) used the adaptive optics system of the National Solar Observatory (NSO) to observe G-band bright points at the diffraction limit of 0.13 arcsec. Langhans et al. (2001) have successfully recorded the G-band spectrum from 430.244 to 430.784 nm of single, isolated G-band bright points.

Plage and network regions consist of magnetic elements, which occur in these regions at a higher than average number density. The enhanced brightness of plage and network regions, especially when located away from disk center is thought to be an important component of solar irradiance variability, since their coverage fraction on the solar surface changes with solar cycle (Foukal & Lean 1988; Fligge et al. 2000). The radiative properties of magnetic elements, or their proxy counterpart, the “G-band bright points”, are therefore of great interest.

How bright are G-band bright points and why are they only visible at highest spatial resolution? Precise measurement of the intrinsic brightness of G-band bright points or their contrast with respect to the continuum radiation is difficult, due to the limited spatial resolution of telescopic observations and due to further degradation by the atmospheric seeing. Berger et al. (1995) report that “G-band observations are seen to give contrast values about a factor of 2 higher than those measured in the continuum” and they estimate an intrinsic G-band contrast relative to the surrounding quiet Sun of maximum 0.5. G-band bright points are typically located at vertices of the granulation pattern — in regions of high abundance also within intergranular lanes. This means that they are located in local minima (troughs) of the continuum intensity, which, at spatial resolution worse than 0.2 arcsec, become rapidly “filled” by the brightness of neighboring granules and the bright point itself (Tittle & Berger 1996). Therefore, G-band bright points are hardly visible in filtergrams with a spatial resolution above 0.2 arcsec.

In this paper, we present results from the computation of synthetic G-band spectra and show, why the contrast of bright points in the G-band is so much higher than it is in the continuum.

2. LTE or NLTE?

G-Band bright points are a manifestation of magnetic elements, which are concentrations of magnetic flux into tube like structures. Magnetic flux tubes have a field strength of the order of 1.5 kG and typically a diameter of 100 km ($\approx 0.15$ arcsec). They rise from the solar surface in vertical direction (due to the action of magnetic buoyancy) and rapidly expand with height because of the exponentially decreasing gas pressure. The magnetic pressure exerted by the field concentration perpendicular to the magnetic lines of force is balanced by a reduced density of its atmosphere relative to the surrounding, embedding atmosphere. This partial evacuation reduces the opacity of the flux-tube atmosphere and as a consequence, iso-surfaces of optical depth are depressed at the location of the flux tube as schematically indicated in Fig. 1.

At the circumference of the depression hot subsurface material becomes exposed to free space, forming what is called the “hot walls”. The hot walls excessively radiate into the flux tube (radiative channeling, see Cannon 1970; Trujillo Bueno 1990; Hasan et al. 1999) entailing two consequences. First, the flux-tube atmosphere becomes heated through the radiative influx by about two
The $\tau_c=1$-surface is depressed at the location of the magnetic flux tube, which exposes hot subsurface material at the circumference of the depression, where excessive radiative cooling takes place.

hundred K with respect to the surroundings at equal geometrical height (Steiner & Stenflo 1990; Fabiani Bendichio et al. 1992). Second, an excess of ultraviolet radiation (in comparison to the quiet Sun surroundings at equal optical depths) escapes from the hot walls.

According to Rutten (1999), conventional wisdom holds that magnetic elements brighten in the G-band because the CH lines cause radiation escape somewhat higher up in the atmosphere, where the flux tubes are heated, e.g., by the radiative channeling effect, while in deep layers from where the continuum radiation escapes, the temperature elevation is less pronounced. This reasoning is based on the approximation of local thermodynamic equilibrium (LTE).

However, Rutten (1999) argues that this explanation is wrong and that actually the low dissociation energy of CH of only 3.5 eV would make this molecule liable to photodissociation by the near-UV photons from the hot walls, thereby weakening the CH absorption line in the G-band. This then clearly is an effect of non-local thermodynamic equilibrium (NLTE). He also points out that CO, which forms in the middle and upper photosphere curtails the formation of CH, restricting its presence to the deep photosphere (Mount, 1975). This would explain, why granulation, as seen through a G-band pass filter, looks very similar to images taken in the nearby continuum.

In this paper we adopt the LTE assumption and test, if existing model atmospheres for magnetic elements are capable of reproducing the observed enhanced contrast in the G-band, leaving an estimate of the deviation from LTE to a forthcoming paper. The test is carried out by computing synthetic G-band spectra of different model atmospheres for magnetic elements, which then are multiplied with the transmission profile of a realistic G-band pass filter. From these data we finally compute the theoretical contrasts in the G-band and, for comparison, in the nearby continuum.

3. Synthetic G-band spectra

As a first test example we here use the model atmospheres for network (net) and plage (p1a) flux tubes by Solanki & Brigeljvice (1992) and compare the
resulting spectra with that of the quiet Sun model atmosphere (qS) of Maltby et al. (1986). The latter is modified in that the chromospheric temperature increase is removed by linear extrapolation of the photospheric temperature profile. This modification is necessary since the analysis is carried out in LTE, in which case the chromospheric temperature inversion would lead to spurious spectral line core emission reversals of absorption lines. The models of Solanki & Brighlejić should be particularly good in the deep photospheric layers to which the following analysis applies. Figure 2 shows the temperature as function of optical depth for the three models.

In a next step we use the radiation transfer code PHOENIX of Hauschildt et al. (1996, 1997, 1999) and Baron & Hauschildt (1998) in order to analyze these atmospheres and compute synthetic G-band spectra from each model atmosphere, assuming all models to be plane-parallel. This code includes a master line list of 47 million atomic and up to 350 million molecular lines. The molecular line list includes the HITRAN92 list (Rothman et al. 1992) as well as Kurucz’s CD 15 data (Kurucz 1993). Additional lists complete or replace HITRAN92 or CD 15, whenever they are judged more reliable, like the CO vibration-rotation line list by Goorvitch & Chackerian (1994a,b), or the CN line list by Jørgensen and Larsson (1990). Data for $^{12}$CH and $^{13}$CH are taken from Kurucz’s CD 15 with solar isotopic abundances. The line profiles are assumed to be depth-dependent Voigt profiles (or Doppler profiles for very weak lines only). Details of the computation of the damping constants and the line profiles are given in Schweitzer et al. (1996).

Figure 3 shows the synthetic G-band intensity spectrum from 430 nm to 431.2 nm computed from the quiet Sun model qS (thick curve) together with
the corresponding observed spectrum as given in the "Jungfraujoch atlas" of Debouille et al. (1973). We have found the fit to be best when equating the continuum intensity of the synthetic spectrum with the intensity value 11000 of the "Jungfraujoch atlas". The agreement between the two spectra is impressive: all the observed lines and blends are correctly reproduced and the rms deviation in the wavelength range from 430 nm to 431.2 nm is less than 0.1.

4. G-band contrast

Figure 4 shows the synthetic G-band spectrum computed from the network model, \textbf{net} (thick curve), together with that from the quiet Sun model, \textbf{qS} (thin curve), both multiplied with the transmission profile of a G-band pass filter. The \textbf{net}-model shows throughout a higher intensity because it is hotter than the quiet Sun model, but the difference is more pronounced within spectral lines than in the continuum. This can be quantified by computing and comparing the contrast between the two atmospheres, once integrated over the entire bandpass filter and once for the theoretical continuum at 430 nm.

The continuum and G-band contrast are given respectively by

\[
C_c = \frac{(I_{bp,c} - I_{0,c})}{I_{0,c}} , \quad C_G = \frac{\int T_G(I_{bp} - I_0) \, d\lambda}{\int T_G I_0 \, d\lambda} .
\]

(1)

Here, index $c$ refers to the nearby continuum, index $bp$ to the flux tube atmosphere (bright point), and index 0 to the quiet Sun model atmosphere. $I$ designates the intensity and $T_G$ is the G-band transmission profile. The integration is taken from 429.5 to 431.5 nm.

For the network model atmosphere, \textbf{net}, we obtain in combination with the quiet Sun model, \textbf{qS}, a continuum and G-band contrast of

\[C_{c,\text{net}} = 0.34, \quad \text{and} \quad C_{G,\text{net}} = 1.26 .\]

Thus, the contrast in the G-band is a factor of 3.7 higher than the corresponding value in the continuum. This huge contrast enhancement in the G-band is due
to the absorption lines, which are more sensitive to changes in temperature than the continuum is. The enhancement factor of 3.7 is considerably higher than the factor of two reported by Berger et al. (1995). However, the present value of $C_G$ and $C_c$ is computed without taking into account image degradation by instrumental or seeing effects. On the other hand, we consider the network atmosphere to be plane-parallel, where in reality its lateral extension is only of the order of a pressure scale height. Thus we do not take the “hot walls” into account, which would further increase the contrast.

Using the double Gaussian representation of Title & Berger (1996) for the intensity profile of a bright point located within intergranular space and us-

Figure 5. Double Gaussian intensity profiles and degradation with a Gaussian PSF of increasing HWHM, $c$. Thick curves refer to the G-band contrast, $C_G$, thin curves to the continuum contrast, $C_c$. The dashed curve shows $C_G/C_c$. The contrast values for $c = 0$ correspond to $C_{c,\text{net}}$ and $C_{G,\text{net}}$. 

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ing a Gaussian estimate for the point spread function (PSF), Fig. 5 shows the reduction in maximal G-band and continuum contrast as a function of image resolution, \( c \), i.e., the half-width at half maximum (HWHM) of the PSF. Note that at a spatial resolution of 0.2 arcsec, the intrinsic G-band contrast of 1.26 is reduced to 0.1 and the one for the continuum from 0.34 to -0.075. Interestingly, the contrast enhancement, \( C_G/C_c \), of initially 3.7 first increases with image degradation and changes sign at the position, where the maximum continuum contrast of the bright point embedded in the intergranular lane depression vanishes. This demonstrates that the ratio of G-band to continuum contrast, \( C_G/C_c \), is a quantity, not very suitable for measurement since it is extremely seeing dependent.

When using a combination of qS with p1a, the continuum and G-band contrasts are given respectively by

\[
C_{c,p1a} = -0.22, \quad \text{and} \quad C_{G,p1a} = 0.25.
\]

5. What causes the enhanced G-band contrast?

Figure 6 shows the partial gas pressure (which is directly proportional to the abundance) of CH, CO, and CN as a function of optical depth \( \tau_{500\,\text{nm}} \) for the quiet Sun model qS (thick curves) and the network model atmosphere net (thin curves). Note that CO increases with height much steeper than CH and it increases monotonically in case of qS. Thus, CO curtails the formation of CH,
which passes through a maximum at around $\tau_{500\text{ nm}} = 0.2$, restricting its presence to the deep photosphere. This maximum is shifted to about $\tau_{500\text{ nm}} = 0.01$ in the hotter network atmosphere, below which depth ($\tau_{500\text{ nm}} > 0.01$), the partial pressure of CH is markedly reduced due to collisional dissociation. For $\tau_{500\text{ nm}} < 0.01$ the two atmospheres do not deviate strongly with respect to CH.

From this, we conclude that the strong contrast enhancement of network bright points in the G-band is due to the depletion of CH in the deep layers of the network atmosphere with respect to the surrounding quiet Sun at equal optical depth. This shortfall weakens the CH lines in the G-band of the network bright point, allowing more of the continuum to "shine through the thinned forest" of CH-lines. This effect must be separated from that of the elevated temperature of the network model to brighten spectral line cores (according "conventional wisdom"), which works without change in the abundance of any species. This latter effect is less important for the G-band contrast enhancement.

A behavior very similar to CH is exhibited by CN so that we expect contrast enhancements similar to the G-band for example in the CN bandhead at 388.3 nm (as was observed by Chapman 1970). Also note that CO shows an even stronger deviation of the two atmospheres for $\tau_{500\text{ nm}} > 0.01$.

6. Conclusion

Computing synthetic G-band spectra from model atmospheres of the quiet Sun and network and plage magnetic flux tubes, we have shown that the G-band contrast relative to the quiet Sun surrounding is 1.26 and 0.25 for network and plage magnetic elements, respectively. These values are much higher than the corresponding contrasts in the continuum of 0.34 and -0.22. We have shown that the enhanced contrast in the G-band is a consequence of CH depletion in the deep photospheric layers of the hotter flux-tube atmospheres, which is due to collisional dissociation. This process weakens the CH-lines within the flux tube, allowing more of the continuum to "shine through the thinned forest of CH-lines" across the G-band.

We cannot falsify the conjecture of Rutten (1999) that photodissociation by UV-radiation from the hot walls may be an important mechanism of G-band contrast enhancement, since the present computation is in pure LTE. However, such an additional process would even further increase the G-band contrast, which is already much higher than the maximal intrinsic value of 0.52 derived from observations (using a correction on the basis of a double Gaussian model and a Gaussian PSF) by Title & Berger (1996). Also the contrast enhancement factor of $C_{G\text{ net}}/C_{C\text{ net}} = 3.7$ derived in the present investigation is much higher than the reported observed factor of 2.0, although this is not a well defined quantity. The inclusion of the hot-wall radiation by a two-dimensional radiation transfer instead of the here applied assumption of plane-parallel atmospheres would further increase the contrast values. All this indicates that collisional dissociation is a sufficiently efficient process for producing the observed G-band contrast enhancement and that photodissociation from hot-wall UV-radiation probably plays only a minor, or at most equally important role.

The relative high G-band contrast (in absolute and relative terms) of the synthetic spectra, which would be further increased when taking hot wall radia-
tion and photodissociation into account, leads us to the conjecture that the flux tube model atmosphere net of Solanki & Brögger (1992) is too hot in its deep photospheric layers.

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