Evidence for the impact of stellar activity on the detectability of solar-like oscillations observed by *Kepler*

W. J. Chaplin[1], T. R. Bedding[2], A. Bonanno[3], A.-M. Broomhall[1], R. A. García[4], S. Hekker[1,5], D. Huber[2], G. A. Verner[6], S. Basu[7], Y. Elsworth[1], G. Houdek[8], S. Mathur[9], B. Mosser[10], R. New[11], I. R. Stevens[1], T. Appourchaux[12], C. Karoff[13], T. S. Metcalfe[9], J. Molenda-Żakowicz[14], M. J. P. F. G. Monteiro[15], M. J. Thompson[9], J. Christensen-Dalsgaard[13], R. L. Gilliland[16], S. D. Kawaler[17], H. Kjeldsen[13], J. Ballot[18], O. Benomar[12], E. Corsaro[3], T. L. Campante[13,15], P. Gaulme[12], S. J. Hale[1], R. Handberg[13], E. Jarvis[1], C. Régulo[19,20], I. W. Roxburgh[6], D. Salabert[19,20], D. Stello[2], F. Mullally[21], J. Li[21], W. Wohler[22]

ABSTRACT

We use photometric observations of solar-type stars, made by the NASA

[1]School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

[2]Sydney Institute for Astronomy (SIfA), School of Physics, University of Sydney, NSW 2006, Australia

[3]INAF Osservatorio Astrofisico di Catania, Via S.Sofia 78, 95123, Catania, Italy

[4]Laboratoire AIM, CEA/DSM – CNRS – Université Paris Diderot – IRFU/SAp, 91191 Gif-sur-Yvette Cedex, France

[5]Astronomical Institute, "Anton Pannekoek", University of Amsterdam, PO Box 94249, 1090 GE Amsterdam, The Netherlands

[6]Astronomy Unit, Queen Mary, University of London, Mile End Road, London, E1 4NS, UK

[7]Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520-8101, USA

[8]Institute of Astronomy, University of Vienna, A-1180 Vienna, Austria

[9]High Altitude Observatory and, Scientific Computing Division, National Center for Atmospheric Research, Boulder, Colorado 80307, USA

[10]LESIA, CNRS, Université Pierre et Marie Curie, Université Denis Diderot, Observatoire de Paris, 92195 Meudon cedex, France

[11]Materials Engineering Research Institute, Faculty of Arts, Computing, Engineering and Sciences, Sheffield Hallam University, Sheffield, S1 1WB, UK

[12]Institut d'Astrophysique Spatiale, Université Paris XI – CNRS (UMR8617), Batiment 121, 91405 Orsay Cedex, France

[13]Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark

[14]Astronomical Institute, University of Wrocław, ul. Kopernika, 11, 51-622 Wrocław, Poland

[15]Centro de Astrofísica and Faculdade de Ciências, Universidade do Porto, Rua das Estrelas, 4150-762, Portugal

[16]Space Telescope Science Institute, Baltimore, MD 21218, USA

[17]Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA

[18]Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, CNRS, 14 av E. Belin, 31400 Toulouse, France

[19]Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain

[20]Instituto de Astrofísica de Canarias, E-38200 La Laguna, Tenerife, Spain

[21]SETI Institute/NASA Ames Research Center, Moffett Field, CA 94035, USA

[22]Orbital Sciences Corporation/NASA Ames Research Center, Moffett Field, CA 94035, USA

Kepler Mission, to conduct a statistical study of the impact of stellar surface activity on the detectability of solar-like oscillations. We find that the number of stars with detected oscillations fall significantly with increasing levels of activity. The results present strong evidence for the impact of magnetic activity on the properties of near-surface convection in the stars, which appears to inhibit the amplitudes of the stochastically excited, intrinsically damped solar-like oscillations.

Subject headings: stars: oscillations — stars: interiors — stars: late-type – stars: activity – stars: magnetic field

1. Introduction

Solar-type stars show "solar-like" acoustic oscillations that are intrinsically damped and stochastically excited by near-surface convection (e.g., Houdek et al. 1999; Christensen-Dalsgaard 2004; Samadi et al. 2007). It is now well established that magnetic structures in the solar photosphere are strong absorbers of acoustic (or p-mode) oscillations (Braun et al. 1987, 1988; Braun & Birch 2008). A strong magnetic field can diminish the turbulent velocities in a convectively unstable layer (e.g., Proctor & Weiss 1982; Cattaneo et al. 2003) and this can affect the driving of acoustic modes (e.g., Jacoutot et al. 2008). In solar-type stars, the presence of a fibral magnetic field (Gough & Thompson 1988; Goldreich et al. 1991; Houdek et al. 2001) may become sufficiently strong to affect not only the properties of the p-mode propagation, but also the turbulence of the convection by reducing its magnitude with increasing stellar activity, thereby reducing the amplitudes of the oscillations.

The amplitudes (i.e., the square root of the total powers) of solar p modes are observed to decrease with increasing levels of solar activity (Chaplin et al. 2000; Komm et al. 2000). The decrease observed from solar minimum to solar maximum is about 12.5 % for modes of low spherical degree, l (Chaplin et al. 2000; Gelly et al. 2002; Jiménez-Reyes et al. 2003), which are the modes that are detectable in observations of solar-type stars. García et al. (2010) recently uncovered the first evidence for changes in p-mode amplitudes associated with a stellar activity cycle in another solar-type star, from *CoRoT* satellite data on HD49933.

HD49933, and the other F-type stars observed for asteroseismology by *CoRoT*, have activity levels that are not disimilar to those of the active Sun, as discerned from levels of variability in the lightcurves arising from rotational modulation of starspots and active regions (Mosser et al. 2005; 2009a). The same is true for the F5 star Procyon, as measured in both radial velocity (Arentoft et al. 2008) and photometry (Huber et al., 2010). However, the G-type dwarf HD175726, which was also observed by *CoRoT* (Mosser et al. 2009b), shows much higher levels of activity but barely detectable solar-like oscillations. Mosser et al. speculated that the lower-than-expected amplitudes might have resulted from suppression by high levels of intrinsic magnetic activity. Here, we use the unprecedented large ensemble of oscillating solar-type stars observed by the NASA *Kepler Mission* to search for evidence of this effect in a large number of stars.

In addition to searching for exoplanets (Borucki et al. 2010; Koch et al. 2010), *Kepler* is providing large quantities of high-quality data for the asteroseismic investigation of stars, as part of the *Kepler* Asteroseismology Investigation (Gilliland et al. 2010a). Photometry of a subset of these stars is being made at a cadence that is rapid enough to allow investigations of oscillations in solar-type stars, where dominant periods are of the order of several minutes (Chaplin et al. 2010, 2011a; Christensen-Dalsgaard et al. 2010; Metcalfe et al. 2010). During the first seven months of science operations just over 2000 stars were observed for one month each as part of an asteroseismic survey of the solar-type part of the color-magnitude diagram. Solar-like oscillations have been detected in about 500 stars, increasing by a factor of about 25 the number of solar-type stars with detected oscillations.

The large number of solar-type stars in this *Kepler* ensemble makes possible the statistical study of intrinsic stellar properties and trends, in what is a homogenous data sample of unprecedented quality. Here, we use results on the ensemble to conduct a statistical study of the impact of stellar activity on the detectability of solar-like oscillations.

For this study we have used two simple measures of variability in the *Kepler* lightcurves as proxies of the levels of stellar magnetic activity, including one measure suggested by Basri et al. (2010a, b) from their survey of activity levels in more than 100,000 stars observed in 30-min (long) cadence by *Kepler* during its first month of science operations. We study a subset of about 2000 solar-type stars having short-cadence *Kepler* data and test if the distribution of observed variability differs for stars that do, and do not, have detected solar-like oscillations.

2. Data and Analysis

We use asteroseismic results on solar-type stars that were observed by *Kepler* during the first seven months of science operations. About 2000 stars, down to *Kepler* apparent magnitude $Kp \simeq 12.5$, were selected as potential solar-type targets based upon parameters in the *Kepler* Input Catalog (KIC; Batalha et al. 2010, Koch et al. 2010). Each star was observed for one month at a time in short-cadence mode (58.85 s; see Gilliland et al. 2010b).

Time series were prepared for asteroseismic analysis in the manner described by García et al. (2011), using procedures that work on the raw lightcurves. Lightcurves prepared for the Transiting Planet Search pipeline are not appropriate for use here since phenomena associated with stellar variability are suppressed or removed to aid planet detection (Jenkins et al. 2010).

Different teams analyzed the prepared lightcurves to attempt to detect signatures of solar-like oscillations (see Huber et al. 2009; Mosser & Appourchaux 2009; Roxburgh 2009; Campante et al. 2010; Chaplin et al. 2010, 2011b; Hekker et al. 2010; Karoff et al. 2010; Mathur et al. 2010). Most of the applied detection techniques relied on extracting signatures of the near-regular frequency separations of the solar-like oscillation frequency spectrum, while others searched for signatures of the Gaussian-like power excess due to the oscillations. Verner et al. (2011) present a detailed comparison of the results returned by the different pipelines on the *Kepler* lightcurves, finding reassuring levels of agreement between the results. We demanded that at least two of the asteroseismic data analysis pipelines returned consistent results on a star for it to be flagged as a solid detection for use in this paper. A total of around 500 stars were flagged as having detected solar-like oscillations. The signal-to-noise ratio in the oscillations required for a detection was $\gtrsim 0.1$, as defined by the ratio of the maximum power spectral density of the smoothed oscillation envelope relative to the estimated background at the frequency of maximum oscillations power. This threshold level allows an unambigous detection of the signature of the large frequency separation, and identification of a significant power excess due to the oscillations.

For each star that was analyzed, we used two simple metrics of variability as proxies of the stellar surface activity, as determined from direct analysis of the prepared lightcurves. For both, we first applied a low-pass filter to remove the oscillation signal smoothing each lightcurve with a one-hr-long boxcar. For one metric, we measured the maximum absolute deviation of each smoothed lightcurve from its mean. This simple measure of variability is what Basri et al. (2010a) call the "range", and here we label it $r_{\rm hr}$. Basri et al. smoothed long-cadence (29.4 min) *Kepler* lightcurves with a 10-hr boxcar. We tested the effect of smoothing our short-cadence lightcurves on timescales ranging from 1 hr up to 1 d, but found no significant impact on our results. As our second variability metric we use what García et al. (2010) referred to as a "starspot proxy". We measured the standard deviation about the mean (i.e., the RMS) of each smoothed lightcurve, and we call this metric $\sigma_{\rm hr}$.

Neither of the measures, as defined above, takes explicit account of the apparent magnitude of the target. We would expect there to be a magnitude-dependent correction to $r_{\rm hr}$

and $\sigma_{\rm hr}$ on account of the changing contribution due to shot noise, although the effect is small. We specified the required corrections using the "minimal noise" model for *Kepler* in Gilliland et al. (2010b). The RMS noise, σ, per $\Delta t = 58.85$-sec integration is given by

$$\sigma = \frac{10^3}{c}\left(c + 9.5 \times 10^5 (14/Kp)^5\right)^{1/2}\ \text{ppt}, \qquad (1)$$

where $c = 1.28 \times 10^{0.4(12-Kp)+7}$ detections per cadence, and Kp is the *Kepler* apparent magnitude. Since the time series are smoothed with a 1-hr (3600-sec) boxcar, the additive correction that must be removed from $\sigma_{\rm hr}$ is just $\sigma(\Delta t/3600)^{1/2}$. The correction for $r_{\rm hr}$ was calibrated with Monte-Carlo simulations, and found to be $\sim (2/3)\sigma$.

Since our aim is to understand the impact of stellar activity on the detectability of the solar-like oscillations, we ignored those stars whose lightcurve variability could be attributed to another phenomenon, e.g., eclipsing binaries, and classical pulsators at the hot end of the sample. The fraction of eclipsing binaries that we removed ($\sim 1\,\%$) is in line with the rate of occurence of binaries in the *Kepler* field of view, as determined by Prša et al. (2010) down to $Kp \sim 16$.

3. Results

The top two panels of Fig. 1 plot the range, $r_{\rm hr}$, and the RMS, $\sigma_{\rm hr}$, as a function of $T_{\rm eff}$. Points in black are stars with detected solar-like oscillations. The bottom two panels plot the metrics with the *Kepler* apparent magnitude, Kp, as the independent variable. The dotted lines follow the additive corrections (see above).

Our range plot in Fig. 1 is very similar to the corresponding plot in Basri et al. (2010), which shows results on just over 100,000 stars observed during the first full month of *Kepler* science operations. The data have a lower-limit envelope that has its minimum at approximately solar temperature. The lower limit of the envelope shifts to higher levels of variability at lower and higher temperatures.

It is also apparent from Fig. 1 that the cloud of points for stars *with* detected solar-like oscillations (black points) is clustered toward lower levels of variability. We see no detections above $r_{\rm hr}$ of $\approx 20\,$ppt, and $\sigma_{\rm hr}$ of $\approx 10\,$ppt. The cloud of points for stars *without* detected oscillations (gray points) extends to much higher values in both $r_{\rm hr}$ and $\sigma_{\rm hr}$. There are also stars having no detections that nevertheless show the same levels of variability as stars with detections, i.e., at the lower levels of variability the distributions overlap. The apparent gap at $T_{\rm eff} \simeq 5300\,$K in the distribution of stars with detected oscillations is the result of higher numbers of detections at lower $T_{\rm eff}$ from evolved stars at the base of the red giant

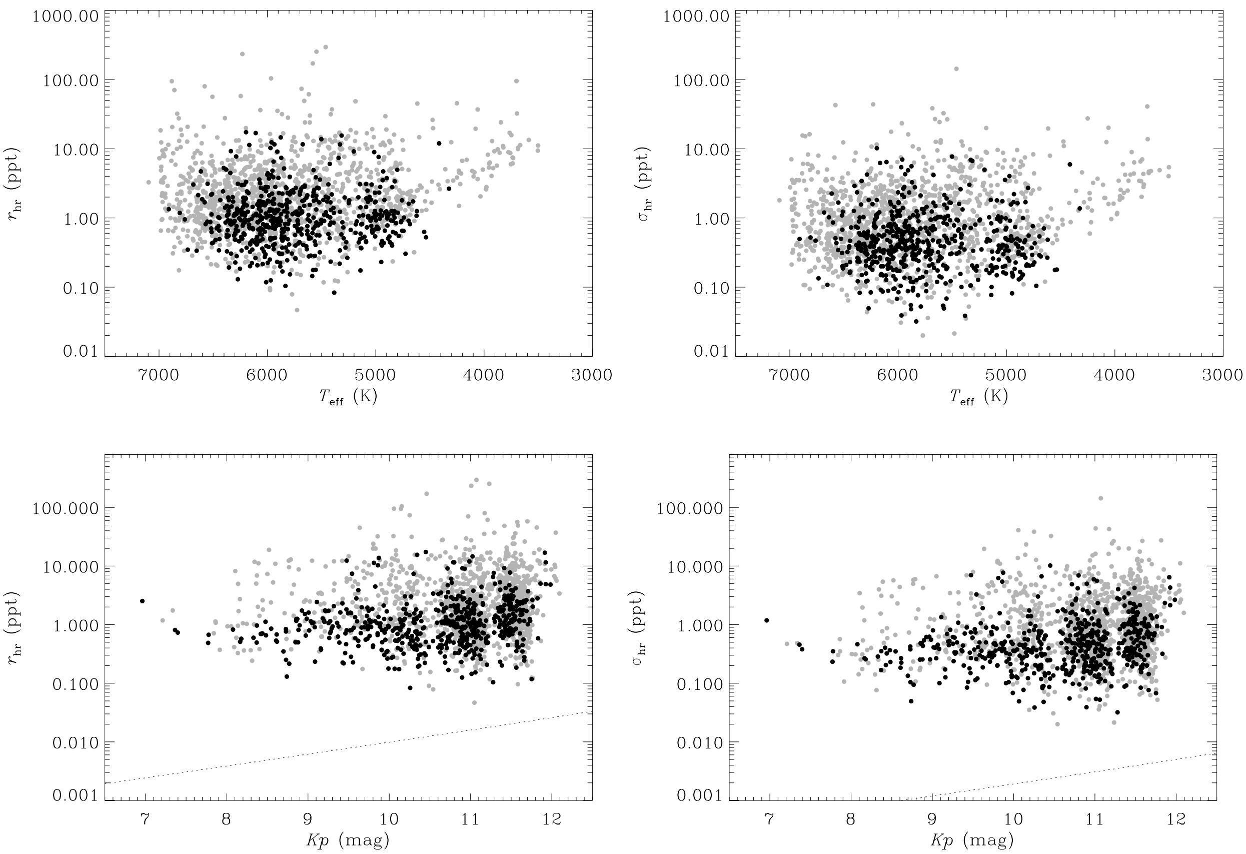

Fig. 1.— Range, $r_{\rm hr}$, and RMS, $\sigma_{\rm hr}$ as a function of $T_{\rm eff}$ (top panels) and *Kepler* apparent magnitude, Kp (bottom panels). Stars with detected solar-like oscillations are plotted in black; stars with no detections are plotted in gray. The dotted lines follow the additive corrections that were applied to $r_{\rm hr}$ and $\sigma_{\rm hr}$ (see text).

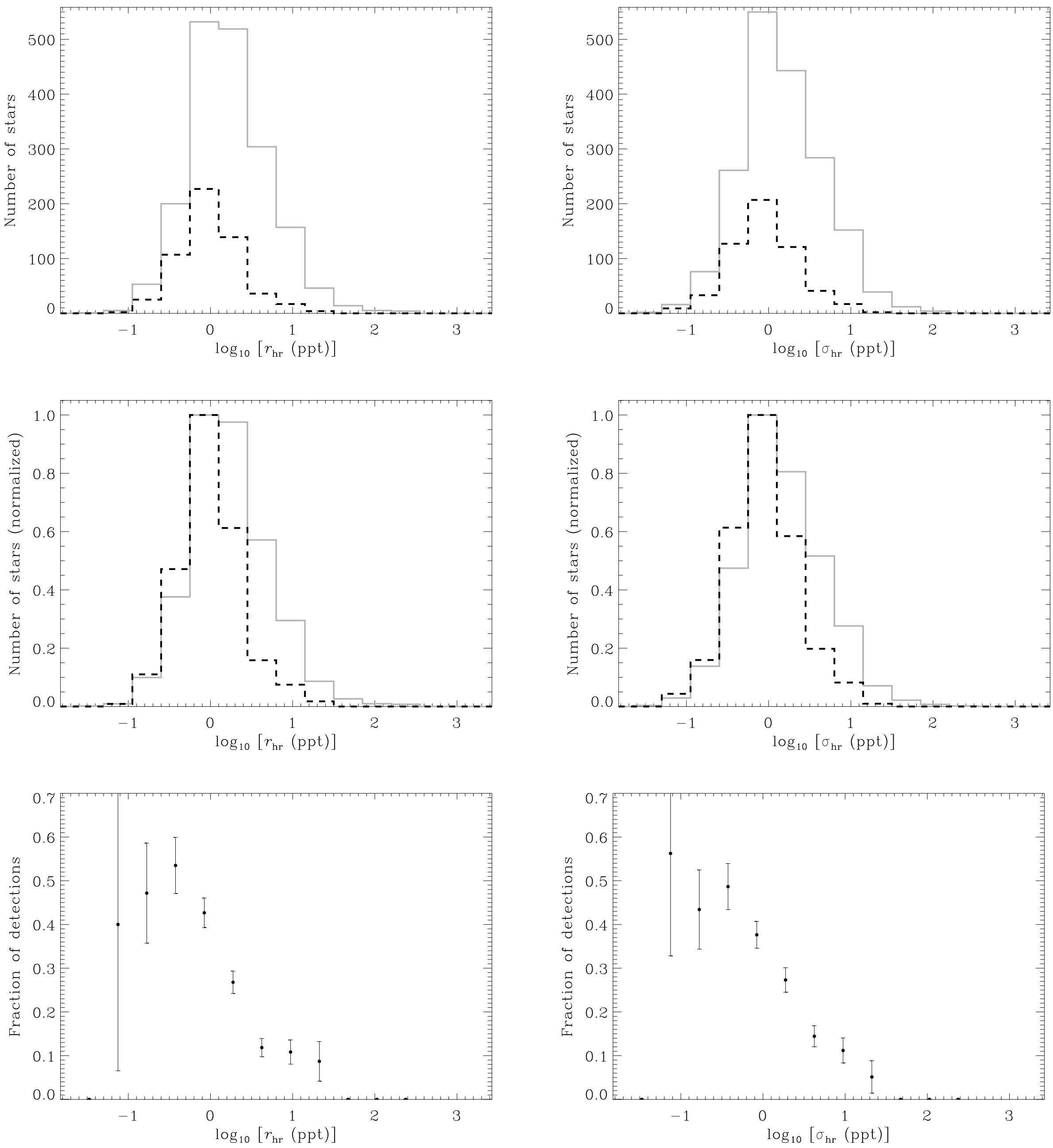

Fig. 2.— Top panels: Histograms of $r_{\rm hr}$ and $\sigma_{\rm hr}$, for all analyzed stars (gray solid lines) and stars with detected solar-like oscillations (black dashed lines). Middle panels: Histograms normalized to a maximum value of unity (same linestyles). Bottom panels: Fraction of stars in each histogram bin showing detected solar-like oscillations.

branch, which have higher oscillation amplitudes than their main-sequence cousins. The distributions in Kp (bottom panels of Fig. 1) are also not smooth, but this effect is present for stars both with, and without, detected oscillations, and it is merely a selection effect arising from the final choice of target stars.

Histograms of $r_{\rm hr}$ and $\sigma_{\rm hr}$ are plotted in the top panels of Fig. 2, for all analyzed stars (gray solid lines) and stars with detected oscillations only (black dashed lines). The middle panels show the histograms normalized to a maximum value of unity to allow a visual comparison to be made of the shapes of the distributions of stars with, and without, detected oscillations. The bottom panels plot the fraction of stars in each histogram bin that show detections, with the errors calculated from Poisson statistics. The histograms in the middle panels show the aforementioned significant deficit of detections at higher levels of variability. The significance of this fall-off is confirmed by the detection ratios in the bottom panels.

Two categories of explanation for the fall-off suggest themselves: one that has its origins in the intrinsic properties of the stars (much the more interesting explanation); or another that is the result of either data-analysis or selection bias issues affecting the detectability of the modes. Let us consider first the possibility that data analysis issues might be the cause.

Sudden discontinuities or large excursions in the lightcurves can affect the appearance of the frequency spectrum of the lightcurves if not treated properly, e.g., as a result of the introduction of a complex overtone structure, or the introduction of frequency-dependent noise, into the frequency range of interest for detection of the oscillations. To test the impact of these effects on our results we selected about 150 stars for which we had successfully detected oscillations, covering a wide range of intrinsic stellar properties and apparent magnitudes. We then picked a subset of 50 stars with high levels of variability, but no detected oscillations. In one set of tests – analyzed using the pipeline described by Hekker et al. (2010) – we added the low-pass filtered parts of the high variability lightcurves to the high-pass filtered parts of the lightcurves with detected oscillations, and then checked whether we could still detect the oscillations. In another set of tests – analyzed using the pipeline described by Huber et al. (2009) – we selected high variability stars at random, and generated synthetic lightcurves comprised of 10 random low-frequency sinusoids with amplitudes selected to ensure that the low-frequency spectra of the synthetic lightcurves matched those of the real stars. These synthetic lightcurves were then multiplied by a random factor – to allow as wide a range of variability to be sampled as possible – and then added to one of the selected lightcurves with detected oscillations. Again, we tested to see whether the oscillations could still be detected. The data-analysis pipelines detected oscillations at all levels of variability (i.e., even in the most extreme cases), and while a modest fall-off of the detection rates was seen at the highest variability (e.g., for $r_{\rm hr} \gtrsim 30\,{\rm ppt}$) this was at nothing like the levels seen in the real *Kepler* data.

Another concern would be that the fall-off is the result of selection bias: for example, that stars showing higher levels of variability also tend to be fainter, on the average, and therefore less likely to show detected oscillations due to higher levels of shot noise. There are certainly more stars at fainter Kp, which we would expect them to more fully sample the underlying distribution of $r_{\rm hr}$ and $\sigma_{\rm hr}$, including the higher values. The bottom panels of Fig. 1 do seem to bear this out. To test the possible effects of selection bias, we ran the detection prediction code developed for use by the *Kepler* Science Team (Chaplin et al. 2011b) on all 2000 targets. This code takes as input the KIC radius, effective temperature and apparent magnitude, and produces as output an estimate of the probability of detection for an assumed length of observation, based on use of scaling relations that know nothing about the possible effects of activity on the amplitudes of the oscillatons. We are interested only in the distribution of predicted detections, and the ensemble is large enough to provide statistically robust results. Those results indicated that the steep fall-off seen in the *Kepler* results cannot be explained by selection bias. There was some fall-off in the predicted fraction of detected oscillations, because there are more stars with high variability that are also faint (see above); but we saw "predicted" detections in stars showing even the highest levels of variability. The results also provided an explanation of why some stars with low levels of variability did not have detected oscillations. The expected success rate of detections was found to be less than 100 %, because noise realizations will in some cases hamper extraction of the oscillation signals. That said, the absence of detections in some of the brightest stars in the sample that show only modest levels of variability is a puzzle. It may be that the inclinations of stars play a role here. The inclination will affect the apparent (i.e., observed) variations seen in $r_{\rm hr}$ and $\sigma_{\rm hr}$, assuming that in solar-type stars those variations are dominated by contributions from active latitudes like for the Sun (e.g., see Knaack et al. 2001; Vázquez Ramío et al. 2010). It could be that some stars with small $r_{\rm hr}$ and $\sigma_{\rm hr}$ are actually intrinsically active stars observed at low angles of inclination (which will reduce the variations observed in the lightcurves).

In summary, we conclude that the steep fall-off in the observed fraction of detections has a stellar explanation.

4. Discussion

The most compelling explanation for the results is that they show evidence for intrinsic stellar (magnetic) activity suppressing the amplitudes of the solar-like oscillations, and hence adversely affecting the detectability of those oscillations. In offering this explanation we assume that the metrics we have used are reasonable proxies of intrinsic levels of stellar activity (see Basri et al. (2010) for further discussion). This certainly seems to be the case for the Sun. We analyzed observations of the bolometric flux of the Sun made by the PMO6 instrument onboard the *ESA/NASA SOHO* spacecraft (Fröhlich et al. 1997). Fig. 3 plots $r_{\rm hr}$ and $\sigma_{\rm hr}$ (filled symbols in each panel) as determined by analysis of independent one-month-long segments of PMO6 data. The gray line in each panel describes a smooth curve through the independent measures, while the dotted line shows the scaled 10.7-cm radio flux, which is an excellent proxy of the global level of magnetic activity on the Sun (e.g., see Chaplin et al. 2007, and references therein). The underlying trends in $r_{\rm hr}$ and $\sigma_{\rm hr}$ clearly follow those in the magnetic activity.

The range varies from about 0.25 ppt to about 1 ppt between solar minimum and maximum. We know that the amplitudes of the low-degree solar p modes are at the same time suppressed by a fraction $\simeq 0.125$ (Chaplin et al. 2000; Gelly et al. 2002; Jiménez-Reyes et al. 2003; García et al. 2010). These solar data in principle allow us to calibrate the expected suppression of oscillation amplitudes due to activity. Here we present a simple estimate for $r_{\rm hr}$.

We assume that the fractional amount by which the amplitudes are suppressed, $\delta A/A$, is a linear function in $r_{\rm hr}$. This is a valid assumption for the solar values, but may of course be questionable at higher levels of activity. There is also the impact of the inclination of the star to consider (see above). With these caveats in mind, we have that

$$\delta A/A \simeq -\left(\frac{0.125}{1.0-0.25}\right) r_{\rm hr} \simeq -r_{\rm hr}/6. \qquad (2)$$

Integration of the above gives the resulting suppressed amplitude, expressed as a fraction of the amplitude expected for no activity (i.e., zero $r_{\rm hr}$):

$$A(r_{\rm hr})/A(0) \simeq \exp\left(-r_{\rm hr}/6\right). \qquad (3)$$

Fig. 4 plots $A(r_{\rm hr})/A(0)$ as a function of $r_{\rm hr}$. At a range of 20 ppt, the prediction is that the amplitudes are suppressed by a factor of almost 30, and it is therefore not surprising that we see hardly any detections in the *Kepler* ensemble at this value, and none above.

The predictions in Fig. 4 are also in agreement with the *CoRoT* results on the active G-type dwarf HD175726 reported by Mosser et al. (2009b). Peak-to-peak variations in the lightcurve, due to rotational modulation by spots, were found to be typically 1 %, so that $r_{\rm hr} = 5$ ppt. Mosser et al. measured amplitudes that were about 1.7-times lower than expected, based on scaling-relation predictions that are calibrated against solar (i.e., low activity) values. Fig. 4 implies that at this $r_{\rm hr}$ amplitudes should be suppressed by a factor of about two, very close to the factor reported by Mosser et al.

Around 100 of the *Kepler* stars showing detected solar oscillations will be observed for periods lasting several months up to a few years. This will in principle allow us to further constrain the effects of magnetic activity on the oscillation amplitudes by measuring changes to the amplitudes, and the resulting detectability of the modes, as activity levels vary in time. An additional 100 stars, selected by the *Kepler* Science Team as possible planet hosts, should show oscillations based on Chaplin et al. (2011b) and will be followed for several months to years.

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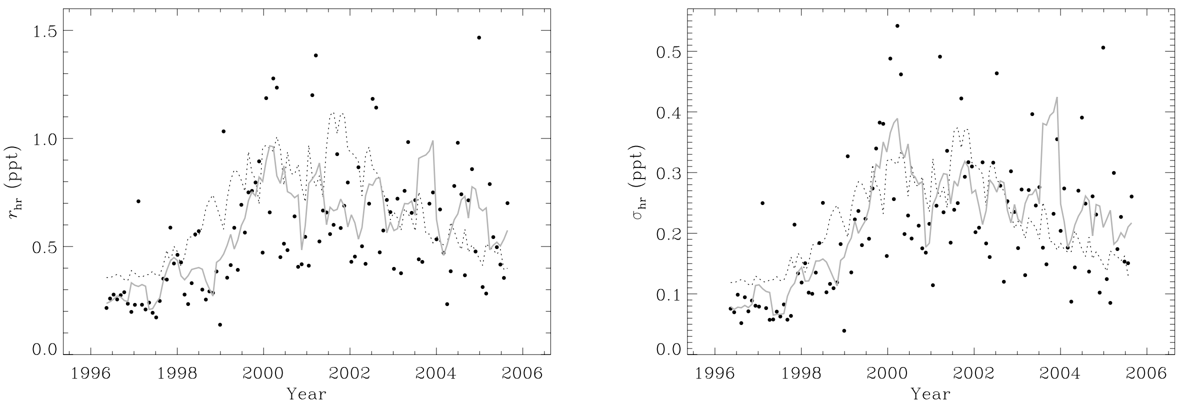

Fig. 3.— Estimates of $r_{\rm hr}$ (left-hand panel) and $\sigma_{\rm hr}$ (right-hand panel) for the Sun (filled symbols), as determined from analysis of one-month-long segments of PMO6 data. Gray lines describe smooth curves through the independent measures, while the dotted lines show the scaled 10.7-cm radio flux.

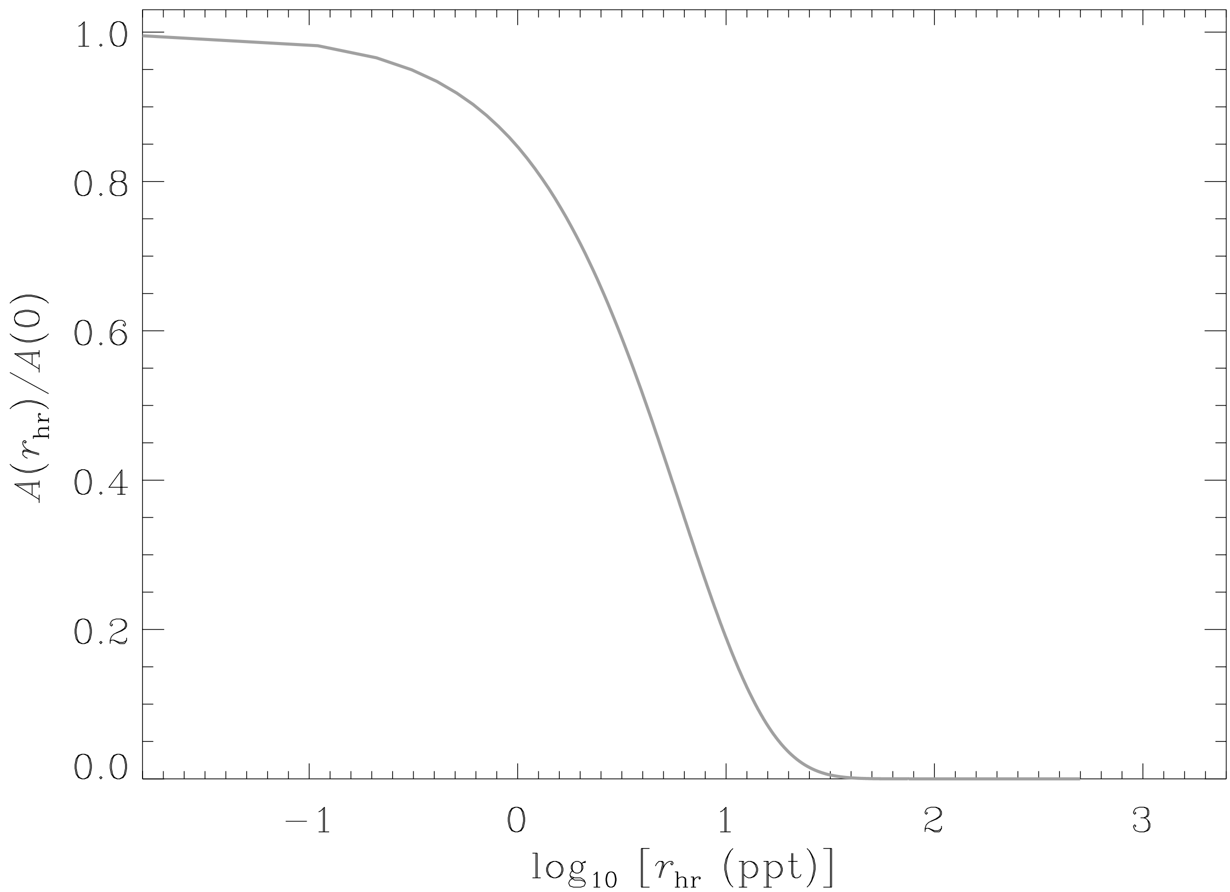

Fig. 4.— A simple model of the suppression of mode amplitudes by stellar activity, with activity measured by the range parameter, $r_{\rm hr}$. The figure shows the expected amplitude versus $r_{\rm hr}$, as a fraction of the amplitude expected for zero activity (i.e., $r_{\rm hr} = 0$).