Chemical abundances in main-sequence stars in open cluster M67

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Summary

The discovery of a solar twin in the open star cluster M67 (Önehag et al. 2011) implies a near-solar chemical composition for the cluster. This study uses high-resolution spectroscopic data of five main-sequence stars in M67 to analyze their abundance of a few key elements and compare results to the solar-twin composition and the composition of field twins (Melendez et al. 2009). The derived composition was also compared to predictions of stellar-structure models including the effects of element diffusion. (Richard, private communication).

It is found that all analyzed elements are, to varying degree, less abundant in the five main sequence stars than in the solar twin. With the possible exception of iron, all derived abundances also fall clearly below the diffusion predictions.
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Background

The stellar photosphere and its properties

A stellar atmosphere is the layer of transition from the interior of the star and the interstellar medium. Roughly, the atmosphere of a solar-type (roughly speaking, a star of spectral type F, G or K) main sequence star can be divided into four layers:

* Sub-photosphere – An optically thick (opaque) layer below the photosphere. Convection handles a significant portion of the energy transport.

* Photosphere – Relatively thin layer that produces the overwhelming majority of the photons that can be detected by an external observer.

* Chromosphere – The layer outside the photosphere, visually dominated by a red Hydrogen emission line. The density decreases with a factor $\sim10^7$ from the bottom to the top.

* Corona – Low-density layer with temperatures on the order of $\sim10^6$ K that can extend several stellar radii out into space.

The thickness of the photosphere varies from star to star, but is typically on the order of a few hundred km. It is related to surface gravity by:

$$g = g_\odot \frac{M}{R^2}$$

where $g_\odot$ is the solar surface gravity of $2.74 \cdot 10^4$ cm/s$^2$, $M$ is the stellar mass in solar masses and $R$ is the radius in solar radii. Through the photosphere, temperature for a typical star differs with more than a factor of 2 between the top and the bottom of the photosphere. This makes it convenient to define an effective temperature that characterizes each star, rather than having to use the temperature at a certain depth. The effective temperature is the temperature of a black body (perfect absorbing body that reflects no light) with the same net output of energy as the star. Mathematically it can be described by the Stefan-Boltzmann's law:

$$\int_0^\infty \mathcal{S}_v \, dv = \sigma T_{\text{eff}}^4$$

where $\mathcal{S}_v$ describes the energy output of the star per area unit as a function of frequency, and the integral describes the net output of the star over all frequencies. The constant $\sigma$ is the Stefan-Boltzmann constant, $\sigma = 5.67040 \cdot 10^{-8}$ W/(m$^2$·deg$^4$).
Spectral absorption

If stars were perfect black bodies, their emitted light spectra would be continuous with a peak at a certain temperature depending on mass and evolutionary stage. However, particles in the stellar atmosphere will absorb photons of certain wavelengths, which will create absorption lines in the spectrum.

Electrons occupy certain energy levels in a particle (atom, ion or molecule). Photons can collide with and become absorbed by the particle, and in the process transfer their energy to an electron. If the photon has energy that corresponds to the gap between two energy levels, the absorbed energy can excite an electron, making it shift to a higher energy level. An electron can also become de-excited, i.e. shifted from a higher energy level to a lower, and the excess energy can be emitted as a photon. This is referred to as a bound-bound transition, as the electron transfers from one “bound” state within a particle to another. The same is also possible (and in many cases, more common) for particle collisions, where the kinetic energy of a particle can be used to excite an electron, or conversely, energy can be transferred from a de-excited electron to a particle. It is particle collisions that make the level populations approach the values one would expect from the thermodynamic properties of the local gas.
Photon energy is related to wavelength by:

\[ E = \frac{h\lambda}{c} \]

where \( E \) is the energy, \( h \) is the Planck constant \((6.632 \cdot 10^{-34} \text{ Js})\), \( \lambda \) is the wavelength, and \( c \) is the speed of light. This means only photons of specific wavelengths are absorbed. The resulting “lack” of photons in that wavelength creates a spectral line. Absorbed photons can be reemitted when the excited electron de-excites, but the de-excitation energy can also be portioned into several emitted photons, or absorbed in particle collisions.

Assuming Local Thermodynamic Equilibrium (LTE), each depth in the stellar atmosphere can be described by only one temperature. The light emitted by each point along the line of sight through the atmosphere is described by a source function, which is temperature dependent. Each source function describes a black-body spectrum, and spectral features such as absorption lines are created by contributions from different source functions at different depths. Without temperature gradients, the source function from all parts of the atmosphere would be the same, and the stellar spectrum would be a simple continuous black-body spectrum. The basic spectrum, without spectral lines, is thus referred to as the continuum.

Fig 2: Simplified graph of energy levels electrons can occupy in an atom.
If the photon has enough energy to push an electron beyond the highest energy level, the electron transits to a free state and leaves the atom altogether, ionizing it. This *bound-free* transition can happen with any photons of higher energy than the atom’s ionization energy, meaning that it does not only lead to the absorption of energy. The same is true for *free-free* transitions, where an already free charged particle interacts with another, and a photon is absorbed to add to one of the particles’ kinetic energy.

Since photons of almost any wavelength can become absorbed in these two processes, they contribute to a *continuous absorption* that affects the overall shape of the continuum. The continuous absorption happens mostly in different species of Hydrogen, as that is the overwhelmingly most common element, and makes up ~70% of the particles in any star. In stars with effective temperatures between ~5000 and 7000 K, the primary absorber in the optical region is H’, negative Hydrogen ions. The electrons required to convert neutral Hydrogen into H’ is supplied by ionized metals.

The spectral lines, however, are formed by photons being absorbed by many different elements. Since the energy gaps in different elements correspond to different photon wavelengths, different spectral lines correspond to different elements. Spectral line strength then becomes an indication of element abundance. With a higher abundance of a certain species of particle in the atmosphere, the corresponding lines will be stronger. This is described in quantitative terms in the curve-of-growth theory.

In addition to particle abundance, however, several other factors affect the strengths and shapes of the spectral lines. Effective temperature, surface gravity, rotation, and turbulence in the stellar atmosphere (both on a small scale and a large scale) are influencing factors.

![Solar spectrum around Mg I](image)

Fig 3:
Portion of the solar spectrum around a Magnesium-line.
Star cluster M67

Messier 67 (M 67) is an open star cluster, located at a distance of roughly 800 pc in the constellation Cancer. Its angular size reaches 30.0’ and it has an integrated visual magnitude of 6.1. An open cluster, as opposed to a globular cluster, contains relatively young stars and holds an orbit closer to the Galactic plane. The stars comprising the cluster have an estimated age of ~4.2 Gyr - derived by evolutionary track modeling - and metallicity close to the solar value (Önehag et al, 2011).

Solar twins in the field and their chemical composition

A solar twin, or solar analog, is as the name implies a star with near-solar spectroscopic properties. They are main sequence stars that differ very little from the sun in effective temperature, surface gravity and overall chemical composition.

A study by Melendez et al. (2009) made an effort to compare element abundances for a number of nearby solar twins in the field (i.e. not cluster member) to solar values. The study found that refractory, dust forming elements (with relatively high condensation temperatures) are generally more abundant in the twins, while volatile elements (with low condensation temperatures) are more abundant in the Sun. The condensation temperature/abundance trend takes a sharp turn at ~1200 K, a feature known as Melendez hockey stick (see Fig 4).

Fig 4: Melendez’ solar field twin abundances for a number of elements, compared to solar abundances. Abundances given on a differential logarithmic scale. Numbers in upper right denote standard deviations of the abundance values of volatiles and refractories, respectively. Abundances plotted as a function of condensation temperature.

Note that the twins have a higher abundance in refractory elements such as Aluminium and a lower abundance in volatile elements such as Oxygen and Nitrogen. Also note the steeper trend at temperatures over ~1200 K. Graph from Melendez et al. (2009).
Solar twin M67-1194

A study by Pasquini et al. (2008) used medium-resolution spectroscopy to search 90 M67 main sequence stars for possible solar twins with focus on assessing effective temperature, which yielded 10 likely solar twin candidates. M67-1194 was selected from these candidates for further study by Önehag et al. (2011) who performed a Line-by-line differential analysis relative to the Sun. It was determined that 1194 is one of the most solar-like star ever analyzed, with stellar parameters virtually indistinguishable from solar values, with the exception of a slightly higher overall metallicity of \([\text{Fe/H}] = 0.023 \pm 0.015\). This metallicity is the best available estimate of the metallicity in the entire M67 cluster, as systematic errors in differential analysis of a solar twin relative to the Sun tend to cancel out.

Interesting is also the fact that the twin does not show a Melendez hockey stick feature when its composition is compared to the Sun. Instead, it shows a much more linear trend, with abundance values fully compatible with solar values (see Fig 5).

The existence of a solar twin in M67 makes the cluster, in which all stars should have been created with near-identical composition, an interesting target for further studies of chemical abundances. This study attempts to analyze the abundances of certain elements for five main sequence stars in M67 and compare them to the solar twin values, to assess whether other stars in the cluster follow the hockey stick trend or the 1194 trend (or neither).

Fig 5: Abundances for solar twin M67-1194, compared with values from Melendez’ field twins, for a number of elements. Abundances given on a logarithmic scale differential relative to the Sun.

Note that the steep increase in abundance for refractory elements in the field twins is absent in 1194.

Graph from Önehag et al. (2011).
Diffusion scenario

When studying stars in different evolutionary stages, there is another factor that can cause the stars’ atmospheric abundances to differ, even if they were born from the same gas cloud. Overall, main main-sequence stars are in hydrostatic equilibrium, but there are still forces acting on the individual particles in the plasma. Atomic diffusion is a process in which gravity and radiation pressure from within the star compete to change the element abundance in the stellar atmosphere. Radiation pressure can push certain particles upwards to the atmosphere, increasing abundance, while gravity can cause other particles to settle inwards, decreasing the surface abundance.

Diffusion is predicted to lead to different element deviations for main sequence stars of different effective temperatures, also; the effect will be larger for some elements and smaller for others, as the radiation pressure is element-specific (see Fig 6).

![Fig 6: Atomic diffusion effects on element abundances, as predicted by Olivier Richard (private communication).](image)

Red curve shows development for stars in different temperatures from cool main sequence (4000 K) to the turn-off point (6000 K), followed by Red Giant Branch-development. Note the large effect on Iron and Magnesium and the smaller effect on Titanium and Calcium. Stars have initial chemical composition identical to solar. The discovery of solar twin M67-1194 constrains the overall initial composition of M67 to values near-identical to solar.

The five main sequence stars in this study have been analyzed for a potential diffusion signature.
From observation to analysis

The road from observed starlight to useful spectral data suitable for analysis is long and not entirely uncomplicated. This section briefly describes the steps that have been taken to process the data to a form that can be readily analyzed.

Observation

The high-resolution (R \approx 47000) stellar spectra used in this study were observed by the ESO-Very Large Telescope (see Fig 7) using the FLAMES-UVES multi-object spectrograph during the spring of 2009. A total of 11 exposures were made during the course of three months. The eight fibers of FLAMES covered solar twin M67-1194, a sky spectrum used for calibration, and six other M67-member stars. Two wavelength regions (REDL and REDU, covering 4800-5800 Å and 5850-6800 Å, respectively) were recorded for each star. One of the stars displayed radial velocity changes and was assumed to be a binary, and was therefore not used for this study. The other five are main sequence stars, a few hundred K hotter than the sun, with slightly lower surface gravities (they will be referred to in this paper as M67-1116, -1221, -1265, -1367, and -1568). Their effective temperatures and surface gravities as used in this study were determined through photometric calibrations, using the latest infrared-flux method (Casagrande et. al, 2011) and provided by Frank Grundahl (private communications, 2011). See appendix for full list of stellar parameters.

Fig 7: Picture of one of the VLT:s at Paranal, Chile, with the moon, Venus and Jupiter visible in the sky background. Image credit: ESO/Y. Beletsky.
FLAMES-UVES is a cross-dispersing spectrograph that uses a two-grating setup to divide the incoming light into wavelength regions, known as spectral orders. Due to the type of grating used, the intensity of each order gets a *blaze distribution*, a Gaussian-like shape with the highest intensity near the middle wavelengths. The spectral orders are recorded in parallel on a Charge-Coupled Detector (CCD). A CCD is a two-dimensional rectangular or square detector with an array of pixels. When a pixel is struck by an incident photon, it forms a charge-hole pair. By shifting the potential barriers between pixels, the charges can be forced to migrate down the pixel rows to the edge of the detector where the charge pulses can be processed and read digitally.

**Data reduction**

The raw data straight from a CCD is impractical to use for a direct analysis, for several reasons. The two wavelength regions are both divided into orders. Each order is blaze-distributed, with an intensity-peak near the middle, and lower intensity near the edges. Another problem caused by the CCD is the pixel-to-pixel variation: different pixels on the detector may vary in sensitivity by several percent, which will give inaccurate intensity shifts in the observed spectrum.

This section details the steps taken to compensate for these problems and further reduce (process) the data to a form practical for spectral analysis.

**Bias subtraction:**

In order to ensure that all measurements yield a positive number of charges in the output data, a *bias potential* is added to the CCD. The same bias is subtracted after the observation to produce the correct results.

**Flatfield calibration:**

To flatten the blaze signatures in each order, a *flatfield calibration* is applied; using a calibration lamp to create a continuous spectrum of the same wavelengths region as the observation covers, a calibration spectrum. The stellar spectrum is then divided by the calibration spectrum, which removes the blaze features and also takes care of the pixel-to-pixel variation. This leaves each spectral order as a normalized and flattened spectrum without the distinct blaze “bulge”. The bias subtraction and flatfield calibration for the data used in this study was performed by Eric Stempels as a part of the study of solar twin M67-1194 (Önehag et al, 2011).
Thorium-Argon calibration:

The scale of each spectral order is given in detector pixels rather than actual wavelengths, which is inconvenient for use in analysis. To create a wavelength scale, an exposure from a Thorium-Argon lamp is made for the same spectrograph and the same CCD used for the stellar exposures. The well-known Th-Ar-lines allow for comparison between CCD pixels and line wavelengths, making it easy to determine which pixels correspond to which wavelengths. This is referred to as a Thorium-Argon calibration. For this project, an original Th-Ar calibration was made for solar twin M67-1194 as a part of the study by Önehag et al. (2011) using IDL-software wavecal (Piskunov). This solution was used as a template to which the calibration for the five main sequence stars was compared, using the same software.

Order merging:

After the Th-Ar calibration, the spectral orders for both wavelength regions need to be merged into one long coherent spectrum. Each order spans a certain wavelength interval, and adjacent orders have a short overlap region. The echelle grating blaze decreases the signal-to-noise in the exposure near the ends of each order. Glue, the IDL-script used to merge the orders, weighs two adjacent orders’ S/N ratio in the overlap region when merging them. For both wavelength regions (REDU and REDL), Glue produces two .fits-files; one containing the spectrum and one containing an error estimate of the merging.
Fig 9: Two orders being merged in IDL-script Glue. Note the overlapping region in which the two orders are weighed based on their S/N-ratio.

**Radial velocity-solution**

The observed stars in the M67 cluster have a radial velocity relative to the observation point on Earth, contributed to by the cluster’s velocity, the stars motion relative to the cluster, Earth’s orbit around the sun, and Earth’s rotation around its own axis. The radial velocity produces a redshift (in case of motion away from Earth) or blueshift (towards Earth) which causes spectral lines to get shifted to higher/lower wavelengths. Since each of the 11 exposures of the stars have been made at different times (sometimes months apart), each exposure will show a different redshift or blueshift. It’s possible to determine this redshift and by extension the radial velocity if spectral lines are compared to a spectrum already adjusted for redshift/blueshift.

This project used IDL script *Rave*, which reads a reference spectrum of the sun and cross-correlates it to the observed stellar spectra. The header – a text file accompanying the spectral file – is then updated to include the calculated radial velocity. In other words, the script does not actually shift the spectrum to compensate for radial velocity; it simply provides the information for how much it needs to be shifted later.
Fig 10: Cross-correlation function describing the radial velocity shift, as derived by *Rave*. The x-axis shows radial velocity shift in pixels, and the y-axis shows the correlation for each shift. The peak at ~28,000 pixels is the best fit according to the cross-correlation.

**Coaddition**

All 11 observations of each star are added together, to give an averaged spectrum with the highest possible S/N-ratio. The spectra are *resampled* in order to make sure that all observations use the same wavelength increments and starting values. Finally, the data pixels were *rebinned*, i.e. two pixels are combined into one “average” pixel, also for the sake of maximizing the S/N-ratio. In this project, the coaddition was performed by Andreas Korn.
Data analysis

The abundance analysis in the project has been performed differentially with regards to the solar twin M67-1194 presented by Önehag et al. (2011). Abundances have been modeled first for the solar twin and then compared to the five hotter main sequence stars.

The Spectrum Investigation Utility (SIU) software (Johannes Reetz, Munich) was used to analyze absorption lines. SIU creates a synthetic model spectrum for a very small wavelength region in and around an absorption line, based on several input parameters.

Input parameters

**Effective temperature** – The temperature of a theoretical black body with the same radius and net energy output as the star. Ranges between 6071 and 6193 K for the five main sequence stars.

**Surface gravity** – The gravity acceleration at the surface of the star, usually given on a logarithmic scale with gravity in cgs-units, log$_{10}$ (g). Ranges between 4.22 and 4.30 for the five main sequence stars. Solar (and solar twin) surface gravity is log$_{10}$ (g)$_{\odot}$ = 4.44.

**Metallicity** – Amount of metals (any element heavier than Helium) in the atmosphere, usually. It is common to use Iron abundance as a proxy for metallicity, as Iron is an easily accessible metal with a complex atomic structure, and many absorption lines in the optical region of the spectrum. It has an influence on the model structure of the models used.

Given on a differential logarithmic scale relative to solar values:

$$[Fe/H] = \log_{10}(N_{Fe}/N_{H})_{\text{star}} - \log_{10}(N_{Fe}/N_{H})_{\odot}$$

where $N_{Fe}$ and $N_{H}$ are the number of Iron and Hydrogen particles, respectively, per unit volume. The unit for the scale is the logarithmic dex-unit.

**Microturbulence** – The velocity differences of random motion of gas in the stellar atmosphere on distances smaller than the mean free path of the photons. Given in km/s. Derived for this study by analysis of five Fe II-lines. Values for the five main sequence stars range between $\xi = 1.30$ and $1.47$ km/s, which is higher than the solar twin value of 0.95 km/s.

**Convolution** – Parameter that emulates a number of different line broadening effects, caused by macroturbulence (representing large-scale motions known as convection), rotation, and the limited resolution of the spectrograph. Derived for each spectral line by iterative fitting of the synthetic spectrum. Typical values for the five main sequence stars $\approx 5$ km/s (formulated as the Full Width Half Maximum of the Gaussian function used).
**Element abundance** – The abundance of the element in question. Given on a differential logarithmic scale, in this study relative to M67-1194 values:

\[
[Fe/H]_{1194} = \log_{10}(N_{Fe}/N_H)_{\text{star}} - \log_{10}(N_{Fe}/N_H)_{1194}
\]

Can also be presented on a \( \log \varepsilon \) scale, which simply compares the abundance of the element to that of Hydrogen, on a logarithmic scale.

\[
\log \varepsilon(X) = \log_{10}(N_X/N_H) + 12
\]

The constant 12 is added to yield positive values (although certain rare elements still have negative \( \log \varepsilon \) abundances). The unit for the scale is the logarithmic \( \text{dex} \)-unit.
Creating the synthetic spectrum

SIU interpolates a model stellar atmosphere in a pre-calculated grid based on the input parameters, assuming Local Thermodynamic Equilibrium (every depth level in the star can be described by only one temperature, with one source function). The light from the stellar interior has the shape of a black-body radiation, until selective wavelengths are absorbed in the atmosphere. SIU calculates the *continuous absorption coefficient* and the *line absorption coefficient*. The former describes the overall absorption over the spectrum, mainly caused by *bound-free* and *free-free* transitions in Hydrogen particles. The latter describes the line-creating absorption caused by *bound-bound* transitions.

The absorption coefficients are calculated for a number of depth points along the line of sight into the star - as different layers of the photosphere contribute to different amounts of emission and absorption - as well as for different wavelengths in the wavelength region of interest. To create the final spectrum, the contributions of layers along the line of sight are integrated together. The values from each point are weighted so that the contributions from different points are attenuated according to depth into the star.

Much of the starlight reaching an observer is contributed to by points not on the line of sight, but instead scattered into it from different directions. Since the absorption the light from these points suffers is different depending on the angle to the observer, the software takes this angular dependence into consideration.

![Fig 11](image_url). An SIU synthetic spectrum fitted to an observed spectral line. Yellow dots are rebinned pixels from 11 co-added observations. Yellow line is synthetic spectrum. The flux on the y-axis is on a relative scale.
Input parameter values

In this study, the effective temperature and surface gravity for each star was taken from a photometric calibration kindly provided by Grundahl (private communications, 2011), using the IRFM from Casagrande et al. (2011) infra-red flux method. The calibration assumes a distance module (difference between absolute and observed magnitude) for M67 of 9.66 (9.80 when extinction is unaccounted for) which is slightly higher than the value from Pasquini et al. (2008), 9.63, and than the value from An et al. (2007) and Sandquist et al. (2004) with values of 9.61 and 9.60, respectively. The iron abundance for the solar twin was taken to be \([\text{Fe/H}] = 0.02\) dex, i.e. slightly higher than the solar value.

The microturbulence values were derived specifically for each star, using an analysis of five Fe II-lines, three weaker and two stronger. Stronger lines are more microturbulence-dependent than weaker, and thus the Fe-abundance derived from them should deviate more than the abundance from the weaker from the actual value when modeled with the wrong microturbulence. When plotting abundance as function of line strength, a good microturbulence approximation will yield a trend with zero slope. The solar twin microturbulence was known to be close to 0.95 km/s, and the twin was therefore used as a reference point. Equivalent width [mÅ] was used as the line strength measurement.

![Graph showing iron abundance plotted as a function of equivalent width for five Fe II-lines for star M67-1568. Abundance given on a logarithmic differential scale with regards to solar twin M67-1194. Different colors show different microturbulence. Lines are linear trends. Dotted blue line shows reference abundance value for solar twin M67-1194. Values given by different lines differ up to as much as ~0.1 dex. In particular, the 5197 Å-line (EW ~ 93) shows higher abundances than the rest of the trend.](image-url)
The three weaker lines: 5325.13 Å, 5414.07 Å, 5425.26 Å
The two stronger lines: 5197.48 Å, 5234.63 Å.

The microturbulence derivation yielded microturbulence values between 1.3 and 1.42 km/s for the 5 main sequence stars.

See Appendix for full list of stellar parameters.

The average iron abundance derived from the five Fe II lines for each star was used as the SIU iron abundance input value for the analysis of other elements.

Finally, the convolution and, most importantly, the abundance values were derived through iterative fitting of the synthetic SIU spectra to observed spectra for the absorption lines in question.

Selecting spectral lines

This study makes an attempt to compare the chemical abundance for five main-sequence stars in the open cluster M67 with diffusion models by Richard (private communication), as well as comparing to the results from the study of Solar twin M67-1194 by Önehag et al. (2011), and the Melendez et al. (2009) study of field solar twins.

With the exception of two Ti II-lines, all analyzed lines were lines that had been analyzed in the study of M67-1194 by Önehag et al. (2011), as their equivalent width was already known for the solar twin, which gives an indication of how strong the lines would be for the other main sequence stars as well. Generally, lines from ionized species of elements were favored over neutral lines, as neutral lines are more sensitive to changes in the input effective temperature, the parameter that is the most difficult to constrain. See section on temperature sensitivity below.

Weaker lines (with equivalent width of ~30 mÅ) were used in favor of stronger, both because weaker lines are less sensitive to erroneous microturbulence values and because they have higher abundance sensitivity, making the analysis more accurate.

The elements analyzed are Iron, Scandium, Calcium, Titanium and Magnesium.
Temperature sensitivity

Elemental abundances derived from spectral lines formed due to absorption from ionized particle species are less sensitive to temperature differences than lines from neutral species. This is related to the fact that for many elements, the ionized species is by far the most common in a stellar atmosphere, which means that an abundance increase in either species (and corresponding decrease in the other) will yield a much larger relative change for the neutral species abundance, and a change in temperature yields different amounts of ionization in an element. Abundances derived from neutral lines can differ with ~0.07 dex for a corresponding change in temperature of 100 K. A temperature sensitivity analysis was performed, to determine how much a different input effective temperature in S1U affects the output abundance.

<table>
<thead>
<tr>
<th>Line</th>
<th>Temperature difference</th>
<th>Abundance difference (averaged from fits for five stars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti I [6258 Å]</td>
<td>+ 50 K</td>
<td>+ 0.04 dex</td>
</tr>
<tr>
<td></td>
<td>+100 K</td>
<td>+ 0.08 dex</td>
</tr>
<tr>
<td></td>
<td>- 50 K</td>
<td>- 0.04 dex</td>
</tr>
<tr>
<td></td>
<td>- 100 K</td>
<td>- 0.084 dex</td>
</tr>
</tbody>
</table>

The neutral Titanium-line displays high temperature sensitivity. 100 K difference in input temperature yields an abundance difference of 0.08 dex, which is almost a factor of ten larger than the change predicted by atomic diffusion theory.

<table>
<thead>
<tr>
<th>Line</th>
<th>Temperature difference</th>
<th>Abundance difference (averaged from fits for five stars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti II [5211 Å]</td>
<td>+ 100 K</td>
<td>0.00 dex</td>
</tr>
<tr>
<td></td>
<td>+ 500 K</td>
<td>+ 0.024 dex</td>
</tr>
<tr>
<td></td>
<td>- 100 K</td>
<td>+ 0.008 dex</td>
</tr>
<tr>
<td></td>
<td>- 500 K</td>
<td>+ 0.064 dex</td>
</tr>
</tbody>
</table>

The ionized Titanium-line displays a much lower temperature-sensitivity. A 100 K increase or decrease is barely enough to shift the abundance even by 0.01 dex. Interestingly, the abundance increases both for increased and decreased temperature of several hundred K. This was not observed to the same extent for any other investigated line.
The other ionized Titanium-line displays similarly low temperature sensitivity. With increased temperature, the abundance increases. With decreased temperature, the abundance decreases slightly, only to increase slightly again with even lowered temperatures.

<table>
<thead>
<tr>
<th>Line</th>
<th>Temperature difference</th>
<th>Abundance difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti II [5418 Å]</td>
<td>+ 100 K</td>
<td>+ 0.01</td>
</tr>
<tr>
<td></td>
<td>+ 500 K</td>
<td>+ 0.06</td>
</tr>
<tr>
<td></td>
<td>- 100 K</td>
<td>- 0.005</td>
</tr>
<tr>
<td></td>
<td>- 200 K</td>
<td>- 0.01</td>
</tr>
<tr>
<td></td>
<td>- 500 K</td>
<td>+ 0.0025</td>
</tr>
</tbody>
</table>

The ionized Iron-line showed low temperature sensitivity. A difference of 100 K gives abundance differences lower than the predicted differences due to atomic diffusion. Notable is that the abundance increase for both increased and decreased temperature that was observed for Titanium II is not present here.

The main goal with the temperature sensitivity check was to determine whether the model is sensitive to temperature changes on the order of 100 K or less. It appears that the ionized lines are insensitive to such changes, as the output abundance differences yielded are less than the investigated predicted diffusion predictions. The neutral lines, on the other hand, are very sensitive, and a small error in the temperature determination of the stars would yield a large error in the output element abundances.
Results

This section gives an overview of the main results of the study. All abundances are stated as compared with M67-1194 ([Fe/H]_{1194}). For detailed information about the abundance of each element in each star, see Appendix.

Iron:

Iron abundances were derived from 5 different Fe II-lines, both in order to determine microturbulence and overall metallicity as SIU inputs, but also because Richard (private communication) predicts a significant difference in Iron abundance between a star in the position of M67-1194 and the five hotter stars of this study (hot star abundance lower by ~0.035 dex). The average derived [Fe/H]_{1194} for all five stars is -0.062 dex. The predicted difference caused by diffusion is smaller, but falls within the standard deviation (0.039 dex).

Some scatter between the stars is present; the highest abundance (M67-1221) is [Fe/H]_{1194} = - 0.044 dex, and the lowest (M67-1568) is [Fe/H]_{1194} = - 0.092 dex. The Fe II-lines have been showed to be temperature insensitive, and the scatter cannot be explained with input temperature errors smaller than several hundred K. With the exception of the hottest star (M67-1568), the abundance seems to increase with increasing effective temperature. Richard predicts the opposite; before the turn-off point from the Main sequence, stars should lower their abundance with increasing temperature. Similarly, apart from the star with lowest surface gravity (M67-1397), the abundance seems to rise with higher surface gravity.
Fig 13. Iron abundance plotted as a function of effective temperature (above) and logarithmic surface gravity (below).
Titanium:

Titanium abundance difference caused by diffusion is predicted to be almost negligible (< 0.01 dex), and as the Titanium-abundance was derived both from two Ti II-lines and from two Ti I-lines, it was possible to determine whether the lines from the two species yielded different results.

Average [Ti/H]_{1194} from all five stars as derived from Ti I-lines is -0.076 dex. The individual stellar abundances differ by as much as 0.07 dex. The diffusion predictions fall outside of the standard deviation (0.033 dex).

The abundance derived from Ti II-lines is noticeably higher; [Ti/H]_{1194} = -0.034 dex. While this value is just barely compatible with the diffusion prediction (standard deviation is 0.032), the star-to-star scatter is large, and two stars (M67-1221 and 1367) fit the predictions exceptionally well, while others (M67-1265 and 1568) fall far outside of it. The Ti II-lines are temperature insensitive, and the scatter is not likely to be due to temperature errors. Any possible trends with increasing temperature or gravity appear less clear than for Iron (see Figs 13 and 14).

Fig 14. Titanium abundance derived from ionized lines (Ti II) plotted as a function of effective temperature (above) and logarithmic surface gravity (below).
The different results from the ionized and neutral lines are not entirely unexpected. Neutral lines have been shown to be more sensitive to temperature discrepancies in the model and the results might indicate that the effective temperature values used are not accurate enough. It’s also possible that the way the line-formation is modeled is inappropriate for Ti I-lines, due to Non-LTE-effects.

Fig 15. Titanium abundance derived from neutral lines (Ti I) plotted as a function of effective temperature (above) and logarithmic surface gravity (below).
**Magnesium:**

Magnesium is expected to show a similar (hot star abundance lower by $\sim 0.035$ dex) difference as Iron. The Mg-abundance was derived from only one Mg I-line. $[\text{Mg/H}]_{1194} = -0.138$ dex, which, with a standard deviation of 0.046 is not even remotely compatible with the expectations. However, since this abundance is derived from a neutral line, it is possible it is affected by the enhanced temperature sensitivity of $\sim 0.07$ dex / 100 K.

**Scandium:**

Scandium abundances were derived (from one Sc II-line) since the field twins of Melendez et al. (2009) and M67-1194 show a slight but significant difference (lower by 0.03 dex for the field twins).

$[\text{Sc/H}]_{1194} = -0.10$ dex, with standard deviation of 0.027. It is, by far, lower than both M67-1194 and the field twins. It differs from M67-1194 with more than three times as much as the field twins do. The standard deviation is relatively small compared to the other analyzed elements, and none of the stars have abundance close to that of the field twins.

**Calcium:**

Calcium abundances were derived from one Ca I-line. Calcium abundances are similar (difference $< 0.01$ dex) for Melendez’ field twins and M67-1194 according to Önehag et al. (2011), and the diffusion predictions from Richard (private communication) state that the abundance should be almost identical (difference $< 0.01$ dex) for the hotter main sequence stars compared to 1194.

The derived abundance, $[\text{Ca/H}]_{1194} = -0.076$ dex, is significantly lower than both predictions. Given the standard deviation (0.037), the observations cannot be reconciled with the expectations from theory. The abundance was derived from a neutral and temperature-sensitive line, which might affect the results.
Conclusions

All derived abundances that have been averaged from all five stars fall well below both the diffusion predictions by Richard (private communication) and the solar twin abundances (see Fig 16 and 17). The stars in question are not solar twins in either temperature or surface gravity, but they are still members of the same cluster and presumably created from gas of the same composition, making the results rather puzzling. The diffusion predictions fail to account for the low abundances of all examined elements, except possibly for Iron. The abundances for the individual stars vary quite a bit, and some stars have Titanium-abundances compatible with predictions, even though the average value is not.

The temperature sensitivity analysis indicates that the ionized lines are less sensitive to temperature differences than neutral lines, and the elements derived from neutral lines differ more from diffusion predictions and solar twin values than those derived from ionized lines. See Fig 16. for Ti and Fe-abundances compared to Richard’s predictions.

The abundance of Iron and Titanium for individual stars can possibly be related to effective temperature and surface gravity (see Figs 13, 14 and 15), but these trends remain somewhat unclear, and with data from only five stars, they are difficult to verify.

Initial chemical composition: solar; Age: 3.7 Gyr

Fig 16: Iron and Titanium-abundances for the five main sequence stars compared to diffusion model predictions by Richard.

The presented titanium-value is a mean value from analysis of two Ti II-lines for all five stars, and the iron-value is similarly derived from five Fe II-lines for all five stars. The abundance values compared to a star of solar twin temperature and to predictions for star of ~ 6100 K. Standard deviations are given in gray boxes.
As mentioned above, the abundances for individual stars differ significantly, and different lines of the same element from the same star can show abundance differences of up to 0.08 dex. For the five analyzed Fe II-lines, one line (5197 Å) consistently shows higher values than the other four, for all stars, possibly caused by a significant blend (nearby lines affecting the shape of a line) by the surrounding wavelength region.

Due to time constraints, more lines could not be analyzed. Further studies should attempt to verify the low abundances by deriving data from more lines per element. Some elements that have here only been analyzed using neutral lines should be tested for a possible abundance difference between neutral and ionized lines.

Fig 17: Titanium and Scandium-abundances compared with Melendez’ solar twins and M67-1194. Titanium value is a mean value based on analysis of two Ti II-lines for all five stars. It’s significantly lower than the abundances for both Melendez’ field twins and the M67-twin. Scandium abundance, derived from analysis of one Sc II-line, is at -0.10, too low to fit in the graph.
Appendix

Stellar parameters

<table>
<thead>
<tr>
<th>Star</th>
<th>Effective temperature $T_{\text{eff}}$ [K]</th>
<th>Surface gravity Log(g) [log cm/s$^2$]</th>
<th>Metallicity $[\text{Fe/H}]$ (std dev) [dex]</th>
<th>Microturbulence [km/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1194 – solar twin</td>
<td>5787</td>
<td>4.44</td>
<td>0.3</td>
<td>0.95</td>
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<tr>
<td>1116</td>
<td>6112</td>
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<td>1.30</td>
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<td>1.30</td>
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<td>6071</td>
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<td>1.37</td>
</tr>
<tr>
<td>1367</td>
<td>6130</td>
<td>4.22</td>
<td>-0.0180</td>
<td>1.37</td>
</tr>
<tr>
<td>1568</td>
<td>6193</td>
<td>4.24</td>
<td>-0.0620</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Table 1: Stellar parameters used in spectrum modeling for all involved stars. Metallicity is given in logarithmic scale where the solar value is 0. The solar twin metallicity value was adopted from Önehag et al. (2011) (mistakenly rounded to 0.03 dex rather than 0.02 dex, but analytical difference is negligible). The metallicity and microturbulence parameters are derived from an iterative Fe II-line analysis. Effective temperature and surface gravity taken from photometric study by Grundahl (2011).

Chemical abundance – Iron, derived from 5 Fe II-lines

- FeII 5325 Å = [-0.05 -0.05 -0.10 -0.03 -0.12];
- FeII 5414 Å = [-0.05 -0.03 -0.10 -0.02 -0.07];
- FeII 5425 Å = [-0.10 -0.03 -0.10 -0.06 -0.10];
- FeII 5197 Å = [-0.02 -0.01 -0.07 0.02 -0.03];
- FeII 5234 Å = [-0.09 -0.05 -0.12 -0.06 -0.12];

<table>
<thead>
<tr>
<th>Star</th>
<th>Abundance $[\text{Fe/H}]_{1194}$ [dex]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1116</td>
<td>-0.0580</td>
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<tr>
<td>1221</td>
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</tr>
<tr>
<td>1265</td>
<td>-0.0760</td>
</tr>
<tr>
<td>1367</td>
<td>-0.0480</td>
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<tr>
<td>1568</td>
<td>-0.0920</td>
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<tr>
<td>Average</td>
<td>-0.0624</td>
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</tbody>
</table>

Table 2: Iron abundances of the five main sequence stars, averaged from an analysis of five Fe II-lines. Abundances are presented in differential logarithmic scale where the solar twin value is 0.
Chemical abundance – Titanium, derived from 2 Ti I-lines

\[ \text{TiI 6258 Å} = [-0.11 -0.04 -0.11 -0.1 -0.05]; \]
\[ \text{TiI 6261 Å} = [-0.11 -0.03 -0.10 -0.04 -0.07]; \]

<table>
<thead>
<tr>
<th>Star</th>
<th>Abundance [Ti/H]_1194 [dex]</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>1568</td>
<td>-0.060</td>
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<tr>
<td>Average</td>
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Table 3: Titanium abundances of the five main sequence stars, averaged from analysis of two Ti I-lines (Note; neutral, un-ionized Titanium). Abundances are presented in differential logarithmic scale where the solar twin value is 0. The abundances are in all but one case much lower than what is expected by diffusion, and much lower than values derived from analysis of lines from ionized Titanium, see table below.

Chemical abundance – Titanium, derived from 2 Ti II-lines

\[ \text{TiII 5211 Å} = [-0.03 0.00 -0.05 0.02 -0.05]; \]
\[ \text{TiII 5418 Å} = [-0.05 -0.01 -0.09 -0.02 -0.06]; \]

<table>
<thead>
<tr>
<th>Star</th>
<th>Abundance [Ti/H]_1194 [dex]</th>
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</thead>
<tbody>
<tr>
<td>1116</td>
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<tr>
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Table 4: Titanium abundances of the five main sequence stars, averaged from analysis of two Ti II-lines (Note; Ionized Titanium). The abundances are presented in differential logarithmic scale where the solar twin value is 0. The abundances for a few of the stars are what is expected from diffusion, although others have slightly lower abundance. The abundances in general are significantly higher than the values derived from lines from neutral Titanium, see table above.
Chemical abundance – Magnesium, derived from an Mg I-line

\[ \text{MgI 6318 Å} = [-0.17 -0.09 -0.19 -0.09 -0.15]; \]

<table>
<thead>
<tr>
<th>Star</th>
<th>Abundance [Mg/H]_1194 [dex]</th>
</tr>
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<tbody>
<tr>
<td>1116</td>
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<td>1221</td>
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<tr>
<td>1265</td>
<td>-0.190</td>
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</table>

Table 5: Magnesium abundance of the five main sequence stars, from an analysis of an Mg I-line. The abundances are presented in differential logarithmic scale where the solar twin value is 0. The abundances are much lower than the solar twin values. See discussion section for possible explanations.

Chemical abundance – Scandium, derived from an Sc II-line

\[ \text{ScII 6245 Å} = [-0.11 -0.08 -0.14 -0.07 -0.10]; \]

<table>
<thead>
<tr>
<th>Star</th>
<th>Abundance [Sc/H]_1194 [dex]</th>
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<tbody>
<tr>
<td>1116</td>
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<td>1221</td>
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<td>1568</td>
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<td>Average</td>
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</table>

Table 6: Scandium abundance of the five main sequence stars, from an analysis of an Sc II-line. The abundances are presented in a differential logarithmic scale where the solar twin value is 0. The abundances are much lower than those of the M67-solar twin, and also lower than values for nearby solar twins presented by Melendez et al. (2009)
Chemical abundance – Calcium, derived from a Ca I-line

CaI 6166 Å = [-0.08 -0.03 -0.13 -0.06 -0.08];

<table>
<thead>
<tr>
<th>Star</th>
<th>Abundance [Ca/H]_1194 [dex]</th>
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<tbody>
<tr>
<td>1116</td>
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<td>1568</td>
<td>-0.080</td>
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<tr>
<td>Average</td>
<td>-0.0760</td>
</tr>
</tbody>
</table>

Table 7: Calcium abundance of the five main sequence stars, from analysis of a Ca I-line. The abundances presented in a differential logarithmic scale where the solar twin value is 0. The abundances are much lower than those of the M67-solar twin for three of the stars, and still significantly lower for the other two. See Discussion section and Temperature sensitivity section for reasons why the use of a neutral, un-ionized may possibly have affected the results.
Referenser


- J. Meléndez, M. Asplund, B. Gustafsson, D. Yong; *The Peculiar Solar Composition and its Possible Relation to Planet Formation* (2009)

- David F. Gray; *The Observation and Analysis of Stellar Photospheres,* Third Edition; Cambridge University Press; First published 2005

- Olivier Richard; private communications

- Frank Grundahl; private communications
Glossary

**Black Body:**
A perfect absorbing body that reflects absolutely no light. Emits a completely continuous spectrum with net energy output and peak wavelength dependent only on temperature. No real objects are perfect black bodies, but stars can in some cases be approximated as such.

**Blaze distribution:**
Spectral feature of a wavelength order detected where the light is distributed with high intensity near the middle wavelengths of the order with low intensity near the edges.

**Blend (line-):**
The shape of a spectral line is affected by a nearby spectral line. Might affect the modeling of the synthetic spectrum.

**Bound-free transition:**
An atom or ion absorbs energy – from a photon, for example – and an electron is ejected from the particle. Leads to ionization when it happens to a neutral atom or already positive ion.

**Bound-bound transition:**
An atom or ion absorbs energy – from a photon, or a collision with another particle – and one of its electron rises to a higher energy level. The opposite, an electron descending to a lower energy level and the atom or ion disposing of the extra energy – in a photon, for example – is also an example of a bound-bound transition.

**Continuous absorption:**
Large-scale absorption across the entire stellar spectrum, for photons of any wavelength.

**Convolution:**
SIU input parameter that emulates the line-shaping effects of macroturbulence, stellar rotation, and the limited resolution of the spectrograph.

**Cross-dispersion:**
A process in which two grating/prism-setup in a spectrograph splits the incoming light into a spectrum, and then splits the spectrum into wavelength regions – orders - which are transmitted in parallel.

**CGS-units:**
A system of units based on using centimeters, grams and seconds as measurements of length, mass and time, respectively, while the ordinary SI-units use meters, kilograms and seconds.
Curve of Growth-theory:
A model describing how a spectral absorption line changes with increasing abundance of the absorbing particle. Initially, the equivalent width increases linearly with the abundance, but when the stellar atmosphere becomes saturated with the element, the line growth drops to a lower rate, asymptotic to a constant value. If the abundance is increased further, the optical depth of the wings of the spectral line increase, and when they become significant compared to the absorption coefficient, the line growth rate increases again.

Diffusion:
Process in stellar atmospheres that alter the atmospheric chemical composition through an interplay of gravitational settling (that causes certain particles to sink down into the star) and radiation pressure (that pushes other particles outwards).

Distance module:
The difference between the apparent magnitude (measured from Earth) and the absolute magnitude (magnitude on a distance of 10 pc) of an astronomical object. Describes the distance to the object.

Effective Temperature:
The effective temperature of a star is the temperature of a black body with the same net energy output as the star.

Evolutionary track modeling:
Deriving properties of a star by looking at models for stellar evolution.

Equivalent width:
Property of spectral lines, used to describe their strength. Equals the width of a rectangle with length from the continuum level of a stellar spectrum to the level of zero intensity that has the same area as the area inside the spectral line.

Free-free transition:
A free charged particle interacts with another particle, and a photon is absorbed as the charged particle increases its kinetic energy, or emitted as the particles decreases its kinetic energy.

Globular Cluster:
Star cluster with tightly gravitationally bound, old, red stars. Such clusters tend to move in orbits in the galactic halo.
Local Thermodynamic Equilibrium (LTE):  
A state in which there is no net mass or energy flow in any direction. Often a convenient approximation for a local volume in a stellar atmosphere, as it allows every depth level in the atmosphere to be described by only one temperature.

Main sequence star:  
The Main sequence is a stage in a star’s life where it is fueled by fusing Hydrogen nuclei into Helium. Stars spend the biggest portion of their lives on the main sequence. Followed by the turn-off point, and Red giant development. Synonymous with Dwarf Star.

Microturbulence:  
The motion of gas in the stellar atmosphere on distances smaller than the mean free path of photons. Affects the size and shape of spectral lines.

Macroturbulence:  
The motion of gas in the stellar atmosphere on large scales (i.e. convection). Affects the shape of spectral lines.

Metallicity:  
The stellar abundance of metals, which here refers to all elements heavier than Helium.

Open Cluster:  
Star cluster with young stars moving in an orbit close to and/or intersecting the galactic disc. Can be disrupted due to gravitational interference from disc attractors (other stars, molecular clouds, etc). M67 is an open cluster.

Photometry:  
The study of the intensity/flux of the light from an astronomical object. Measured over large wavelength-spans, with low spectral resolution (compared to spectroscopy). Useful for determining some basic stellar parameters, such as effective temperature.

Signal-noise ratio (S/N-ratio):  
The ratio between the useful signal (i.e. the actual stellar spectrum) and the noise in the observation.

Star cluster:  
Group of gravitationally bound stars moving together on an orbit in a galaxy. See Globular cluster, Open cluster.

Solar twin:  
Star with Effective Temperature, surface gravity and chemical composition nearly identical to the sun.
**Spectral resolution:**
Measurement of the smallest wavelength region a spectrograph can resolve.
Resolution \( R = \frac{\lambda}{\Delta \lambda} \)

**Spectral type:**
Stars are assigned spectral types/classes (O, B, A, F, G, K, M, from hottest to coldest) based on their color/temperature according to the Morgan-Keenan classification system.

**Spectrograph:**
Device used for spectroscopy. Receives stellar photons from a telescope, and splits light of all wavelengths into a spectrum through the use of gratings and/or prisms.

**Spectroscopy:**
The study of small details and features in the light spectrum of an astronomic object, (i.e. spectral lines).
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Andreas Korn, for all your support and patience.
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Bengt Edvardsson, for your valuable input.
All the other astronomers of Uppsala, for creating a calm and inspiring workplace environment.