Chapter 7

Summary

The project undertaken in this dissertation was to determine if it was possible to observe variability in solar-type stars caused by photospheric manifestations of stellar activity. If so, how does this activity depend on age and spectral type? Prior to this research, the oldest open cluster stars studied on both rotational and long term timescales were in the Hyades, approximately 700 Myr. Older field stars have been studied extensively, but their ages are not well-determined. The clusters chosen for this project are similar in composition to the Sun and span a range of ages that link the younger clusters to the Sun, and even beyond to older stars.

The two main challenges faced in the project were the observational and calibrational difficulty of obtaining high precision measurements and the task of determining which varying stars are varying due to stellar activity. The techniques utilized to deal with both of these challenges were honed in the Phase I observations and analysis. The precision necessary to detect millimagnitude variability required well-exposed images through the BVR filters, high quality sky flats for calibration, and careful differential ensemble photometry. In order to determine if the variability was due to stellar activity, I searched for significant correlations in the fluctuations in each of the colors. Using these techniques, the analysis of the Phase II data yielded a population of active stars in the three younger clusters on the rotational timescale. Applying somewhat adapted analysis techniques to the full eight years of data uncovered a population of stars that are active on the yearly timescale.

The activity level of each of the clusters as a whole did not show any clear trend with age, except that the level of activity in NGC 188 is much lower than the other clusters, on both the nightly and yearly timescales. In the three younger clusters, the general main sequence population shows a distinct positive correlation between fluctuations in the colors. The data for NGC 188 displayed very little correlation, if any. On the nightly timescale, NGC 6819 and NGC 7789 had a considerably lower percentage of active stars than M67. The two young clusters may be in the the Vaughan-Preston gap, with currently relatively low states of activity. The underlying cause of the two activity branches on either side of the gap is unknown, but is believed to be related to a change in the magnetic dynamo within a star. As the stars reorganize their dynamos, the amplitude of activity may be decreased.

The brightness fluctuations in each of the colors observed were larger than the fluctuations due to noise for the main sequence populations in the younger three clusters. This is evidence of many more active stars at lower amplitudes than could be detected individually with the data used in this dissertation. With higher precision measurements, many more stars would be considered to be active.

For each of the clusters, the slope of the correlation between the V and B measurements was larger than the slope of the correlation between the V and R measurements. As discussed in § 1.4, this is a sign of the presence of starspots or faculae on the stellar surfaces, causing the stars to look a little redder or bluer. The RMS brightness fluctuations through each filter for each star showed the same tendency: the slope of the correlation between the RMS V and RMS B fluctuations was larger than the slope of the correlation between the RMS V and RMS R fluctuations.

On the nightly timescale, the three younger clusters did not show a trend in the fraction of active stars by spectral type, which is contrary to the expectation that younger stars are more active. The RMS brightness fluctuations (the activity index) increased with spectral type for the main sequence stars in each of the clusters. Activity on the yearly timescale was also distributed across spectral types for NGC 7789 and NGC 6819. Both M67 and NGC 188 had few active stars on this timescale.

A significant fraction of A and early F stars showed variability on both the nightly and yearly timescales. The average RMS fluctuations are relatively quite large, on the order of 10 mmag. These stars had been previously thought to be quite stable.

The RMS brightness fluctuations on the nightly timescale for the G stars in the project agreed well with data for stars of other ages in the literature. A power law was fit to the amplitude of variability as a function of age, resulting in a $t^{-0.48\pm0.12}$ relation, similar to the Skumanich power law.

The mean RMS variability presented here for stars on the annual timescale doubles the number of measurements available for stars older than 1 Gyr. A power law is also fit to these data, similar to the nightly data, and a $t^{-1.01\pm0.26}$ relation between activity and age is found.

During these analyses, I selected the stars on the binary sequence of each cluster and examined their behaviors separately. Approximately the same proportion of binary stars was active as was active in the main sequence population, which is contrary to the expectation that the components of binary stars will spin each other up and enhance the activity level of each star. However, the number of binary stars meeting the analysis criterion in the Phase II data was very low, making it difficult to draw any firm conclusions.

I recovered a number of previously known periodic variables in each of the clusters. I also discovered six new periodic variables, and present periods, finder charts, and coordinates for them.

7.1 Individual Clusters

7.1.1 NGC 7789

NGC 7789 is the youngest cluster and therefore would be expected to show the most activity, however, that does not seem to be the case in this analysis. A wide range of spectral types of stars are active on both the rotational and yearly timescales. The analysis on the nightly timescale is hampered by the limited time span of the Phase II data: while the cluster was observed on 23 nights, 22 of those nights fall within a three month period. As discussed previously, the stars may not have had time to change their activity states. The analysis on the annual timescale suffers from large errors; NGC 7789 is the faintest of the clusters in the program, and the images taken through the B filter were underexposed during Phase I. Also, due to the faintness of the stars, the observations do not include many stars of late spectral types, such as K and M. Despite this handicap, many of the stars show trends or other long-term behavior over the eight years at amplitudes considerably larger than the Sun's.

7.1.2 NGC 6819

The analysis on the nightly timescale for NGC 6819 is most significantly affected by the short time span of Phase II. The sixteen nights of observations of the clusters do not sample the behavior of the stars well enough to determine their activity levels. Thus, the stars seem less active than they are. NGC 6819 is the most crowded cluster in the program; the effects of crowding were ameliorated in Phase II with the small field of view of the Loral2 CCD, but the data still have larger errors. Crowding is more of a problem in the analysis on the yearly timescale, since this includes the wide-field data from MLO. Nevertheless, stars in this cluster also show long-term trends over the course of this project.

7.1.3 M67

M67 is the brightest and closest cluster in the program; these two facts mean that the data for this cluster have the lowest errors. This cluster was also observed the most nights during Phase II. M67 is the most active cluster on the rotational timescale in the fraction of active stars and the activity index, but this is partly because any brightness fluctuations in the stars are more easily detectable. On the yearly timescale, very few of the stars are active, and the lightcurves show that the amplitude of any fluctuations and long-term trends is much lower than for the stars in NGC 7789 and NGC 6819.

7.1.4 NGC 188

The oldest cluster, NGC 188 is much less active than the three younger clusters in every analysis. NGC 188 is the second-brightest cluster in the program and is also quite sparse. During Phase II, when it was well-exposed through each filter, the photometric errors were reduced to nearly the level of those for the M67 stars. NGC 188 was observed on 21 nights in Phase II, 20 of which were over a period of four months (rather than the three for NGC 7789 and NGC 6819). These facts indicate that the dearth of activity on the nightly timescale in the NGC 188 stars is a real lack of activity in the stars and not a result of errors. On the yearly timescale, the errors in the data are much larger because the images were often under-exposed, especially through the B filter. Individual stars show larger fluctuations than the stars in M67 over the eight years, but the colors are not as well-correlated as in the other clusters; many of the individual lightcurves are fluctuating simply because of the noisy data.

7.2 Future Work

A number of aspects of the observing program could be improved for the continuation of this research. These include, roughly in order of importance: a wider field of view, improved membership lists, a more stable CCD, and adjustments to the differential ensemble photometry routines.

The Phase II data show that the observational procedure of well-exposed, sequential measurements through several filters is effective in obtaining the high quality data necessary for the program. The primary limitation in the Phase II data is that very few stars were observed because of the 3 arcmin field of view of the Loral2 CCD. During the initial portion of Phase I, images taken using the MLO 1-m telescope with a 14 arcmin field had several thousand stars for the richer clusters NGC 7789 and NGC 6819. The Loral2 images taken using the Perkins telescope contained only a few hundred stars. The lack of stars immediately limits the number of main sequence stars of each spectral type that can be observed, which in turn reduces the significance of any results of the analyses of these stars. The problem of a small field of view is compounded by the fact that not all of the stars in the field are members of the clusters. For example, the Phase II data for NGC 7789 included 242 stars with at least five nights of V observations. However, only 136 of these stars (56%) fell on the photometric main sequence. The long-term data are also affected, because only a relatively few stars near the centers of the clusters will have been observed for the entire eight years of this program.

The question of membership is the next major difficulty. Although I have limited the stars in the analysis to those falling on the photometric main sequence, a small fraction of these stars are still not cluster members. Memberships need to be determined through radial velocity and/or proper motion observations. These data do not exist yet for some of the clusters, and the data that do exist often do not extend to the fainter stars. Because of the relative faintness of the clusters, radial velocity measurements would be difficult at best.

An easier problem to address is that of CCD stability. As noted throughout the dissertation, several of the CCDs had problems. The Navy CCD was noisy and usually did not take suitably precise data. The Loral1 CCD had low-level noise problems that caused me to reject much of the data taken using it. The Loral2 CCD appears more stable than the Loral1, but has often had more drastic problems such as the condensation of unknown substances onto the chip. A more stable CCD would improve the precision of the photometric measurements, which would allow the variability analysis to search for lower amplitude fluctuations and to test if the ensemble errors determined previously are really irreducible.

Finally, some improvements to the *diffmag* program would make the activity search simpler. Most of these changes are of the bookkeeping variety. The annual differential magnitudes in each color need to have their zero points tied to the same season so that no artificial offsets occur between the colors. Another improvement would be to subtract the annual mean differential magnitudes from the nightly mean magnitudes during that year to remove any long-term trends in the data.

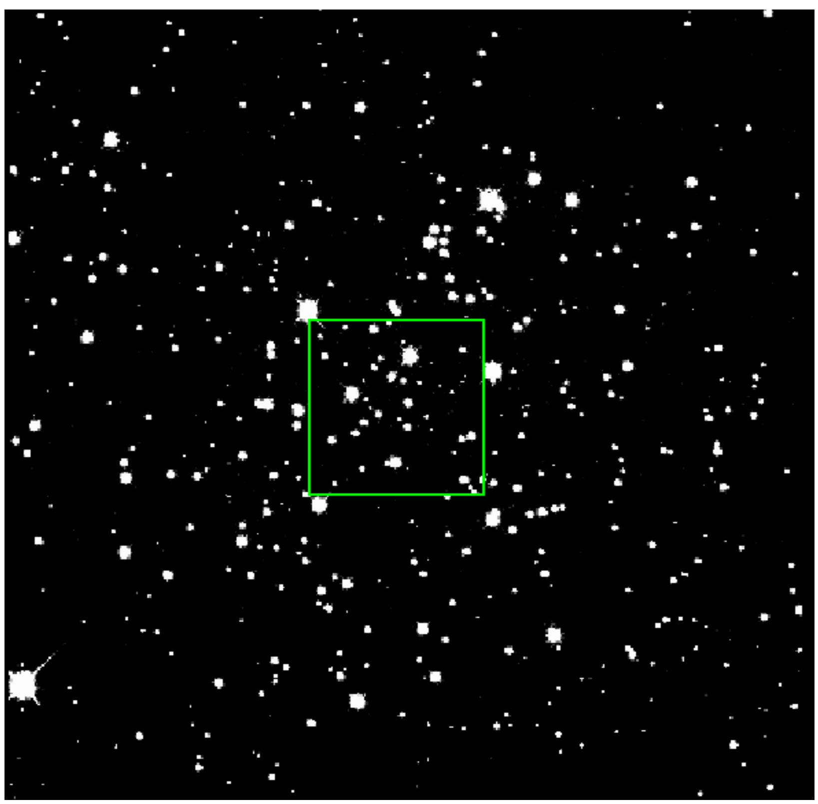

Figure 7.1: A 10 s exposure of M67 taken through the I filter using PRISM on UT 2004 Jan 18. The field of view is 13.65 arcmin square. The Loral2 CCD's 3 arcmin field of view is drawn on the image.

Several of these improvements can be implemented immediately. The Perkins Re-Imaging System (PRISM) built for the Perkins telescope has a much wider field of view (13.65 arcmin) than the other CCDs available at the telescope. The majority of each of the clusters will fit in this field. Figure 7.1 shows an image of M67 taken using PRISM; the approximate field of view of the Loral2 CCD is drawn on the image. The richer clusters may become crowded near the center, causing some stars to be rendered unsuitable for precise photometry, but the addition of many stars closer to the edges of the field should compensate for this. PRISM also has a new CCD that appears to be more stable than the Loral2 in preliminary testing.

Journal Abbreviations

A&A . . . . Astronomy & Astrophysics

A&AS . . . . Astronomy & Astrophysics Supplement

Adv. Sp. Res. . . . . Advances in Space Research

AJ . . . . Astronomical Journal

Ap&SS . . . . Astrophysics and Space Science

ApJ . . . . The Astrophysical Journal

ApJS . . . . The Astrophysical Journal, Supplement Series

ARA&A . . . . Annual Review of Astronomy and Astrophysics

GRL . . . . Geophysics Research Letters

J. Astrophys. Astr. . . . . Journal of Astrophysics and Astronomy

JGR . . . . Journal of Geophysical Research

MNRAS . . . . Monthly Notices of the Royal Astronomical Society

PASP . . . . Publications of the Astronomical Society of the Pacific

Sol. Phys. . . . . Solar Physics

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Massachusetts Institute of Technology, S.B. Earth, Atmospheric and Planetary Science, 1996.

PhD Thesis

Advisor: Professor Kenneth A. Janes. The fraction of stars similar to the Sun in age that display stellar activity has never been determined for stars with well-known ages. The number of active stars is expected to decline with age as the stars spin down. Knowledge of this stellar activity requires long-term, photometrically accurate studies. I undertook a broad-band photometric campaign of old open clusters of solar metallicity using the Mt. Laguna Observatory 1-m and Perkins 1.83-m telescopes to investigate the nature of stellar activity in a statistically significant sample of stars. We found a larger fraction of stars are active than expected, implying that the Sun is a relatively quiet star for its age. Fluctuations on the solar-cycle timescale are seen, but this requires additional observations.

Research Experience

PRISM Instrument

Boston University, 1999 - present: Designed optical wavelength grisms for the Perkins Re-Imaging SysteM (PRISM) instrument built at Boston University for the Perkins 1.83-m telescope at Lowell Observatory. Performed mechanical and optical calibration and integration.

Senior Thesis

Massachusetts Institute of Technology, Spring 1996: Advisor: Professor James Elliot. Analyzed Hubble Space Telescope FOS images of an occultation by Triton in 1995 to measure the thermal structure of its atmosphere.

Undergraduate Research Opportunities Program Projects

Massachusetts Institute of Technology, Summer 1995, Fall 1994, Summer 1994, Summer 1993: Analyzed data from occultations by Triton and 2060 Chiron to learn about their atmospheric structure. Calibrated telescopes and instruments, including flight detectors for the Rossi X-ray Timing Explorer.

Teaching Experience

Lecturing

Boston University Summer Challenge Program I and II: Summer 2003, two sessions. Designed three-lecture astronomy course for high school students.

AS101 - Introduction to the Solar System: Summer 2000, Summer 1999. Designed and lectured full-length astronomy course. Created syllabus, lectures, problem sets, and exams.

Teaching Fellowships

Introductory Courses: Introduction to the Solar System, The Astronomical Universe, Cosmology, from Fall 1996 - present. Laboratory instructor. Designed and revised laboratory curriculum.

Major and Advanced Non-Major Courses: Introduction to the Solar System, Introduction to Stellar and Galactic Astronomy, from Fall 1997 - Spring 2000. Laboratory instructor. Managed long-term observing projects. Designed and revised laboratory curriculum.

Publications

"Variability and Activity Among Stars in Old Open Clusters: NGC 7789", Melissa N. Hayes-Gehrke and Kenneth A. Janes, The Astronomical Journal, 2003, *in revision.*

Hayes-Gehrke, M. N., & Janes, K. A. "Variability in Old Open Clusters on the Solar Cycle Timescale." 2003, *American Astronomical Society Meeting #203, poster.*

Skiff, B. & Hayes-Gehrke, M. "Comet 2002 S1." 2002, International Astronomical Union Circular, 7972, 1.

Janes, K. A. & Hayes-Gehrke, M. N. "A Search for Stellar Activity among Old Open Cluster Stars." 2001, Bulletin of the American Astronomical Society, 33, 1388.

"Separation of a Double Star from Hubble Faint Object Spectrograph Data." Melissa N. Hayes, MIT S.B. Thesis, 1996.

Awards

American Association of Physics Teachers award for excellence as a teaching fellow, 2003.

Teaching Fellow of the Year, Boston University Astronomy Department, 1999.

Professional Public Service Activities

Presenter for Boston University Astronomy Department Public Open Night at Coit Observatory, Summer 2003, Summer 1998, Summer 1997.

Boston University Graduate Science Day, 2001, poster: "Perkins Re-Imaging SysteM Instrument," Hayes-Gehrke, M. N., Janes, K. A., & Clemens, D. P.

Mentor for Pathways at Boston University, 2000.

Boston University Graduate Science Day, 2000, poster: "Optical Observations of Stellar Variability in Star Clusters," Hayes-Gehrke, M. N., & Janes, K. A.

Boston University Graduate Science Day, 2000, poster: "An Optical Survey of Nebulae and Galaxies," Eldredge, D. E., & Hayes-Gehrke, M. N.

Computer Skills

Programming: C, Fortran.

Packages: IRAF, IDL, Zemax Optical Design Program, LaTeX.

Teaching References

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