HgMn stars: new insights

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Abstract. Recent results obtained by various authors on the properties of HgMn stars are reviewed. Substantial progress has been achieved in the study of abundances and isotopic anomalies. The results about the magnetic fields and membership in multiple systems suggest further directions of investigations to be followed in view of answering the question of the development of abundance peculiarities in HgMn stars.

Key words: Stars: HgMn – Stars: abundances – Stars: magnetic fields – multiple stars

1. Introduction

Recent years have seen a renewed interest in HgMn stars. The main objective of studies of HgMn stars is to provide new, better observational data for the theorists investigating the mechanisms responsible for abundance anomalies in these stars. Much spectroscopic work was devoted to elemental abundance analyses. About 30 papers on abundances in individual stars and in samples of stars appeared in the last three years. Good studies of the correlations between elemental abundances and fundamental parameters are crucial for the understanding of the physical processes taking place in HgMn stars. On the other hand, in the consideration of the physical mechanisms contributing to the development of the wide range of abundance and isotopic anomalies, it is important to know the rôle that magnetic fields play.

Here I wish to discuss some of the observations that deal with the problems of anomalous abundances of the heavy elements Hg and Pt and with the question of the presence of surface magnetic fields. Finally, I shall discuss the results of recent statistics of multiple systems among HgMn stars.

2. Abundance studies

Significant progress in abundance determinations has been achieved in the last years by obtaining observations of increased spectral resolution. The best accurate quantitative studies in the complex ultraviolet region were done with the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope (HST) (Leckrone et al. 1998). The data obtained from space for a small number of HgMn stars has led to the identification of exotic species such as

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Ge, As, Ru, Rh, Pd, Cd, Os, Tl, Pb, Bi, and to the quantitative determination of their abundances. Significant progress in the study of chemical abundances and isotopic anomalies in HgMn stars was made possible by the availability of new atomic data, including laboratory measurements and computations of wavelengths, oscillator strengths, isotope shifts, and hyperfine structure for a variety of elements in different ionization stages. Close collaboration between members of the HST team and atomic physicists allowed the nature of chemical anomalies in the UV region of HgMn stars to be unveiled.

An important result achieved through the studies from space is the finding of discrepancies in abundances derived from different ionization states of the elements Si, S, Co, As, Y, Zr, Pt, Au and Hg. Such abundance discrepancies among ionization states probably result from a vertically stratified distribution of the given element within the observable outer layers of the star. However, it cannot be completely excluded that these discrepancies reflect errors in atomic data or are caused by departures from the LTE ionization equilibrium. The heavy-element peak in the best studied star, χ Lup (= HD 141556), rises sharply to Pt, Au, Hg and Tl, and then falls steeply to Pb and Bi (Leckrone et al. 1998). The isotopic anomalies were studied for the heavy elements Hg, Pt, Tl and Pb. Exciting results were found from GHRS observations of the isotopic shifts in the platinum and mercury lines in the two sharp-lined stars χ Lup and HR 7775. For the star χ Lup, platinum consists of a 50–50 mixture of isotopes ^{196}Pt and ^{198}Pt (Kalus et al. 1998). This result is discrepant with what had been found long ago from a study in the optical region by Dworetsky & Vaughan (1973). They had reported that Pt was present as essentially pure ^{198}Pt, the heaviest isotope. Without laboratory data for isotope shifts in Pt, no spectrum synthesis could be done at that time. Recent observations of χ Lup in the visual at very high resolution, $R = \lambda/\Delta\lambda \gtrsim 100\,000$ (Jomaron et al., Hubrig et al., these proceedings), combined with new data for the wavelengths of isotopic and hyperfine components of Pt II (Engleman 1989), confirm the concentration of Pt in its heaviest isotope.

As for χ Lup, the identified platinum isotope mixture at optical wavelengths for the HgMn star HR 7775 appears to be different from that obtained from ultraviolet transitions (Wahlgren & Dolk, these proceedings; Kalus et al. 1998). Wahlgren & Dolk reported that in this star Hg isotopic shifts vary with the ionization stage.

In agreement with previous works on Hg and Pt (White et al. 1976; Dworetsky & Vaughan 1973; Smith 1997), new determinations of isotopic anomalies in the sample of sharp-lined HgMn stars in the optical region show that in the cooler stars both Hg and Pt are concentrated in their heaviest isotopes (Jomaron et al., Hubrig et al., these proceedings). However, detailed abundance structure of the isotopes does not follow the fractionation model introduced by White et al. (1976) and varies from star to star.

Presently, the principal difficulty involved in interpreting the behavior of the isotopes in HgMn stars is that no combination of gross stellar physical parame-

ters is sufficient to characterize the observed variations of isotopic composition.

In recent years a number of papers on quantitative analyses of individual HgMn stars and of samples of such stars from spectra of moderate resolution have appeared. One survey, based mostly on archival IUE spectra, has been devoted to a study of 26 HgMn stars and 14 normal late B stars, to investigate the group characteristics (Smith & Dworetsky 1993; Smith 1993, 1994, 1995, 1997). The abundances of several elements were shown to be correlated with stellar effective temperature, which suggests that diffusion is operating to modify the atmospheres of HgMn stars. On the other hand, it is not clear how the abundances in HgMn stars are affected by stellar rotation. If we expect that diffusion is operating to modify the atmosphere of HgMn stars, then the extent of abundance anomalies should progressively decrease with increasing rotational velocity. This has not been demonstrated yet. Additional abundance analyses of HgMn stars with different $v \sin i$ values may help to clarify whether there is any correlation of abundance with rotational velocity within the class of HgMn stars. The recent studies of Smith & Dworetsky and Smith once again showed that the HgMn phenomenon is heterogeneous, i.e. within the overall class there are subgroups with star-to-star diversity in abundances (see e.g., Sargent & Searle 1967).

In the past, diffusion has proven a successful mechanism to explain the overall trends of surface compositions of chemically peculiar stars. A challenge to any theory now is to identify a mechanism that accounts for star-to-star variations in chemical composition and isotopic abundance.

3. Magnetic fields

Since no combination of stellar parameters has been found to be sufficient to characterize the variety of the surface composition on HgMn stars, some unrecognized factor should be involved among the necessary and sufficient conditions for occurrence of the HgMn phenomenon. Until recently, the issue of the presence of a magnetic field in HgMn stars remained open, and the rôle that magnetic fields possibly play in the development of anomalies in these stars had never been critically tested. This is a fundamental question whose answer is essential for the understanding of the physical processes taking place in HgMn stars and, more generally, during the formation and evolution of B stars.

Previous searches for magnetic fields in HgMn stars had shown that these stars, unlike classical Ap stars, do not have large-scale organized fields detectable through spectropolarimetry. It has never been ruled out, though, that they might have tangled magnetic fields of the order of a few thousand gauss with no net longitudinal component.

The reinvestigation of the magnetic fields at the present time appears to be promising for several reasons.

First, Mathys & Lanz (1990) suggested that some Am stars may have magnetic fields with a structure more complex than that of the classical Ap stars. The detection of a magnetic field of about 2 kG in the hot Am star o Peg (= HD 214994) through the Stenflo-Lindegren multi-line technique, using the differential broadening of lines having different Zeeman sensitivities raised the question whether the hotter counterparts of Am stars, the HgMn stars, also have magnetic fields with a complex structure not detectable through spectropolarimetry.

Second, the recent development of the moment technique by Mathys (1988, 1993, 1995) has significantly simplified the problem of determination of fields with no net longitudinal component. Successful application of this method to the determination of parameters related to the magnetic field have been presented in a number of papers (Mathys 1993; Mathys 1995; Mathys & Hubrig 1997).

Third, the diagnostic potential of circularly polarized spectra recorded with the Zeeman analyzer of the Cassegrain Echelle Spectrograph (CASPEC) at the ESO 3.6 m telescope has considerably improved. From 1993, the instrumental setup has been modified (see for more details Mathys & Hubrig 1997). The configuration used before allowed to achieve a spectral resolution of $R = \lambda/\Delta\lambda = 18\,000$. With the new configuration spectra can be recorded at a resolving power $R = \lambda/\Delta\lambda = 39\,000$ over the range 5600-6800 Å. The moment technique could be applied to analyze the shapes of spectral lines in high-resolution low-noise spectra.

Our first results of the measurements of magnetic fields in the two SB2 stars 74 Aqr (= HD 216494) and χ Lup with the Zeeman analyzer of CASPEC were published two years ago (Mathys & Hubrig 1995). We applied the moment technique to look for possible differential broadening of spectral lines having different magnetic sensitivities. In this approach, the second order moments of the profiles of a sample of lines of a single ion (namely, Fe II) were measured and their dependence on the atomic parameters characterizing the magnetic line broadening was studied. Our study revealed that the HgMn primary of the system 74 Aqr has a quadratic field of (3.6 ± 0.8) kG. We have also been able to detect a longitudinal field of a few hundred gauss in the secondary component of χ Lup at the $4.6\,\sigma$ level. No quadratic field was detected for χ Lup. However, the standard error of the determination was rather large, 1.25 kG. In follow-up observations of the HgMn stars HD 27376, HD 78316, HD 174933, HD 191110 and χ Lup scheduled two years later, we could measure longitudinal fields of the order of few hundred gauss at levels above $3\,\sigma$ (Hubrig & Mathys 1998). No quadratic field detection could be achieved at a significant level.

Nevertheless, these results do not rule out that the considered stars might have tangled fields. The diagnosis of the quadratic field is difficult and it depends much more critically on the size of the set of lines that can be employed than the diagnosis of the longitudinal field. A straightforward continuation in the study of magnetic fields in HgMn stars would be to reduce the measurements uncertainties. This can be achieved by increasing the size of the sample of lines used to diagnose the magnetic field, that is, observing a wider spectral range,

and by achieving better spectral resolution. In 1996 we could take advantage of the unique performance of the high-resolution echelle mode of the ESO Multi-Mode Instrument (EMMI) at the New Technology Telescope (NTT) on La Silla. Using this instrument, both the wavelength coverage and the resolving power are double of those previously achieved with CASPEC. Out of three HgMn stars observed with this configuration, one, HD 78316, had a quadratic field of 2.7 kG at the $6.3\,\sigma$ level.

The fact that only weak fields are observable in circular polarization while quadratic magnetic fields of kG order are probably present most likely means that the field has a fairly complex structure, such that in disk-averaged observations, the contribution of various regions of the stellar surface to the net polarimetric signal mostly cancels out. This does not necessarily imply a very discontinuous field structure like in the sun. Some types of large-scale organization, such as high-order multipoles or toroidal fields (which appear as predominantly transversal), may lead to the observed cancellation. The latter may furthermore be very easily built up in binary systems.

The group of HgMn stars is rich in moderately close binaries, with a frequency of more than 60% (Hubrig & Mathys 1995). It was shown by Zahn (1977) that the tidal forcing of an early-type star in a binary system excites gravity waves at the boundary between the convective core and the radiative envelope. He argued that the torque associated with the excitation of gravity waves is much greater than that associated with turbulent viscosity in the convective core. Zahn (1984) and Goldreich & Nicholson (1989) examined in more detail the manner in which tidal spin-down proceeds in early-type stars. They conclude that tidal despinning to synchronous rotation proceeds from the outside toward the inside of the star. The tidal torque per unit mass varies with depth and latitude in a star, and therefore it tends to induce differential rotation.

We can assume that the rotation observed at the surface of the HgMn stars in binary systems could well be a poor indicator of the total angular momentum $I\Omega$ stored in those stars and that the angular velocity is decreasing outward. Because of the ubiquity of magnetic fields in the universe, we can presume that a weak poloidal field is present in these stars. Then, the toroidal field is produced from the poloidal field by the non-uniform rotation in a characteristic time of only years. The toroidal fields should be able to diffuse slowly outward, or they might be raised to the stellar surface by eruption or meridional flows.

Some binary systems with an HgMn primary are known to have components which definitely rotate subsynchronously (Guthrie 1986) and it is not clear yet how subsynchronous rotation could be achieved. The detection of magnetic fields in a few HgMn stars makes plausible the idea that, like in classical Ap stars, a stellar magnetic field coupling the star with its surrounding can transfer its angular momentum outside the star, and so slow down rotation.

To understand better the nature of HgMn stars, further searches for magnetic fields will be worthwhile. To determine the structure of those fields, the possible variations of the detected fields should be studied.

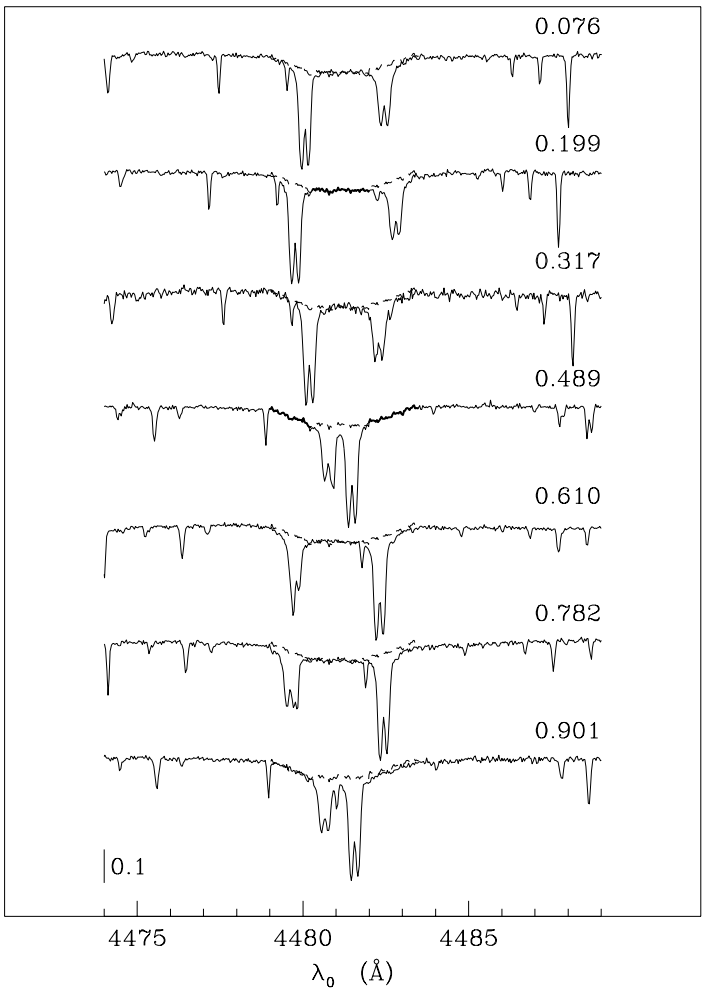

Figure 1. The triple system 74 Aqr at various orbital phases

4. Multiplicity

The last aspect I would like to address is the membership of HgMn stars in multiple systems (i.e., systems with more than two components). The HgMn stars have an unusually high proportion of multiple systems (Hubrig & Mathys 1995). In the presently available catalogue of multiple stars by Tokovinin (1997), which compiles data on 612 stellar systems of different spectral types, I have found four additional systems containing HgMn stars: HD 32964, HD 36881,

HD 58661 and HD 172044. The HgMn stars are restricted to the spectral range B6 to B9. It is intriguing that if the relative frequency of HgMn stars in multiple systems is studied, every third system with the primary in this spectral range involves an HgMn star.

These observational results clearly show that the study of multiple systems with an HgMn component is of prime interest for the star formation theories. To find out which rôle membership of HgMn stars in multiple systems plays for the development of their chemical peculiarities, it would be important to compare the ranges of periods, luminosity ratios, and orbital eccentricities, as well as hierarchy of multiples with the same characteristics as normal late B systems. Especially enlightening will be the determination of chemical composition of the companions in such systems, as well as the search for possible relations between the magnetic fields and the abundance patterns of the various components.

On the other hand, it is still an intricate task to determine the fundamental parameters and chemical composition of the components in binary and multiple systems. One triple system, 74 Aqr, has been presented by Hubrig & Mathys (1994). This system was observed at a resolving power $R = \lambda/\Delta\lambda = 100\,000$ in the spectral region around the line Mg II λ 4481 at various orbital phases (Fig. 1). They are identified in the figure close to the corresponding tracing. Thin lines indicate the contributions of the long-known components of the binary, and broken lines those of the third component. To define the central part of the latter, we have adopted the region comprised between the narrow components at phase 0.199, while its wings have been taken from the regions on each side of the narrow components at phase 0.489 (this procedure is visualized by thick line). The broad feature underlying the strong, sharp Mg II lines of both components appears constant along two orbital periods and seems to be due to a third component. This third component can likely be identified as the companion observed through speckle interferometry, which has an orbital period of $19\overset{y}{.}25$ (Tokovinin 1993). Our observations suggest that its spectral type is similar to or slightly earlier than that of the HgMn primary. However, we have no clue about its possible peculiarity.

5. Conclusions

There has been considerable progress in recent years in our understanding of HgMn stars. However, many gaps still remain in our knowledge of how HgMn stars form and evolve. The mechanisms responsible for abundance anomalies have not been definitely identified yet. Some systematic trends in the abundance data qualitatively support the mechanism of radiatively-driven diffusion. However, it is difficult to determine the mechanisms responsible for abundance anomalies in the absence of accurate observational information about magnetic fields. It is, therefore, essential to settle the issue of the presence of magnetic fields in HgMn stars.

A potentially fruitful area for future research will be the abundance analyses of the components of binary and multiple systems. We have still only relatively rough ideas about the properties of the companions in the systems. On the other hand, such studies are difficult to carry out because most lines of many of the components of a double, triple or quadruple system appear quite weak (2-3% deep) in the spectrum, as a result of the dilution by superposition of their continua. To my knowledge, such an abundance analysis has until now been done only for one multiple system, HD 11905 (Zakharova 1997).

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