SERKOWSKI: At how many positions of the first quarter-wave plate should the observations be made and how the linear polarization produced by reflection from the birefringent material of quarter-wave plate is eleminated?

TINBERGEN: In theory 3 positions are sufficient to determine 2 Stokes parameters plus an instrumental zero. In practice I use 4, but this is an observational detail, not really important from the instrumental point of view. Analysis of the DOLLFUS polarimeter shows that dichroism of the front element is not important, physically the reason is that it produces only linear polarization at a point in the equipment where the information is contained in the circular polarization.

BEHR: With all our 2 cell polarimeters at Göttingen and at ESO in Chile the limiting factor was finally the changing sensitivity of the photocathodes in the order of 10^{-4}. To search this limit or even reach higher accuracy, the proposed way looks quite promising.

Polarization of Young Shell Variables

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Abstract

Stellar polarization between 3000 and 7500 Å has been measured in NGC 2264. Out of 37 stars (including many variables) 4 are definitely polarized, while 3 others show weak polarization. The mean (interstellar) cluster polarization is found to be very small. The highest polarization (4,6 %) is found in a T Tauri star. W 90, a variable below the main sequence, has the highest polarization found among the A and F stars (2,6 %). With the exception of W 46, polarization peaks in the blue implying small particle sizes. A good correlation is found between the size of polarization and (other) shell characteristics. These measurements confirm the recently proposed shells in some pre-main sequence stars which appear to be too faint for their color, but fail to detect any new stars with extensive shells. This suggests that some of the scatter in the color-magnitude diagram amongst the A and F stars is real because of an age spread between 1 and 3×10^6 years.

This is the first of two reports on our investigation of the incidence, variability and composition of circumstellar shells amongst pre-main sequence stars in NGC 2264.

Shell stars often appear polarized due to dust particles aligned in a weak magnetic field or scattering in asymmetric gas or dust distributions. If we expect some correlation between the size of the shell and the polarization of light passing through it, then polarization measurements of the stars in NGC 2264 should help determine the incidence of shells. Such polarization measurements can only be interpreted once a correction for the interstellar contribution is made (if large enough). NGC 2264 is ideally suited for these measurements since the interstellar polarization can be determined from the unpolarized stars in the cluster. Furthermore, the amount of interstellar reddening between us and the cluster has been shown to be small, so that the interstellar polarization should also be small. Finally, membership of the cluster stars has been studied.

The Kitt Peak National Observatory polarimeter attached to the No. 1 36-inch telescope at the Kitt Peak National Observatory was used during eleven nights in January and February, 1971. The polarimeter utilizes a star-sky chopper and a rapidly rotating polarizer. The data is stored in 400 channels. Instrumental polarization was determined from standard stars with near-zero polarization. It was less than 2,0 % in all colors and was subtracted out. Four different filters were used. The UBV filter system used as well as the other equipment, operation and reduction have recently been described by DYCK and SANFORD (1971). Our 7000 A filter consists of a 1 mm RG-5 filter with a shortward cutoff near 6500 A.

An accuracy to 0,1 % in the amount of polarization measured in several colors requires one or more nights of integration for stars fainter than V = 12. To use the maximum number of photons, a preliminary survey of 26 stars without any filter was undertaken. The effective wavelength in the filterless systems lies between the B and V colors.

Out of 35 stars measured, four stars with significant linear polarization stand out. W 46 shows a maximum polarization in the visual region (.90 ± .09 %), while the other three stars peak in the blue: W 90 2.62 ± .19 %), W 139 (4.58 ± .42 %) and W 165 (.85 ± .09 %). Three other stars (W 20, W 107 and W 131 = S Mon) show a $p/\sigma > 5.0$, where p is the average polarization in all colors relative to the cluster means and σ the standard error in p. These three stars also may possess real intrinsic polarization.

What interstellar component in the polarization do we expect? The ratio of the amount of polarization to visual extinction, A_V, has been shown not to exceed the value (HALL and SERKOWSKI, 1963)

$$\frac{p\,(\text{mag})}{A_V} = .065$$

Taking $A_V = 0.2$ mag for the uniform reddening in NGC 2264 and converting p in mag to the amount of polarization, we find that $p < 0.6$ % and a probable value near $p = 0.3$ %. The measured values are also small with the cluster mean between 0.1 and 0.2 % in the visible and blue region. The position angles of the cluster mean at different wavelengths agree extremely well. Nevertheless, we feel that because of the small numbers in relation to their standard errors, the determined means are uncertain. Since the interstellar component does not change our conclusions, no correction was applied.

NGC 2264 is seen projected against an opaque cloud and effects of background nebulosity cannot necessarily be ignored for faint stars in nebulous regions. Although both star and sky were measured close together, the Stokes vectors of the nebulosity may vary considerably over a few seconds of arc. Especially some 15th mag stars may be contaminated by nebulosity (WALKER 1956). Our program was restricted to stars brighter than V = 13.2. To minimize background nebulosity, a small entrance diaphragm of 0.5 mm was used. The nebulosity next to W 90 (V = 12.5 and polarized) was measured separately during the darkest part of our run (during a lunar eclipse!) and the sum of nebulosity and sky found to be negligible. Furthermore, no meaningful polarization difference between the two channels (sky — sky) was detected. Hence we feel that the measured polarization is relatively free of background nebulosity effects.

The measured amounts of polarization in NGC 2264 do not follow a normal distribution. W 46, W 90, W 139 and W 165 show significantly larger polarization than the other cluster stars measured. How do the polarization results compare to other shell indications?

Table 1: Shell Characteristics of Polarized Stars

Star	Luminosity as f (Te)	Abnormal Gravity	H emission	IR excess	Abnormal Δ (b—y), Δ m_1	Light Variability
W 46	Most luminous A star	no	yes	large	yes	no
W 90	Faintest A star, below main sequence	yes	yes LKHα 25	very large	yes	very large
W 139	—	—	yes LKHα 47	—	—	yes
W 165	Faint A star	yes	yes	large	no	likely
Unpolarized Stars	Wide distribution	rare?	rare?	some	rare?	rare

Almost all A and F stars in NGC 2264 have ultraviolet excesses possibly caused by free-free and bound-free emission arising in gas shells. A measure of shell absorption/emission may also be photometrically obtained through a comparison of the strength of the Hβ line and the slope of the Paschen continuum. The Hβ line is affected by line emission while the Paschen continuum may be distorted by non-grey shell absorption. This may be computed from the uvbyβ measurements made by STROM et al. (1971). CRAWFORD (1970) has shown that the β index in normal stars is related to the expected (b — y) through a relation $(b-y)_0 = 2.943 - 1.0\,\beta - 0.1\,\Delta c_1 - 0.1\,\Delta m_1$. In Table 1, the difference between the expected and observed (b — y) as well as m_1 index is indicated. Proper reddening and luminosity (solely as judged from the position in the color-magnitude diagram) corrections have been applied. Δm_1 is also a measure of abnormal line strengths and/or abnormal energy distributions in the blue and yellow regions.

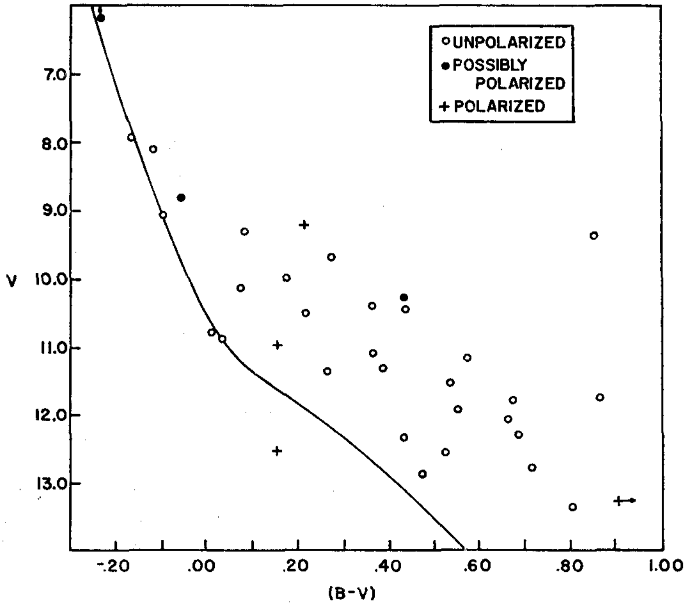

Fig. 1: Position of the polarized and unpolarized stars in the color-magnitude diagram of NGC 2264.

In Table 1, the different shell characteristics of the polarized and unpolarized stars are compared. A few stars show abnormal gravities in the sense that the gravities determined from hydrogen line profiles are not compatible with the apparent stellar position in the color-magnitude diagram (presumably caused by shell absorption). The infrared excess and gravity data were taken from presently unpublished work by STROM, the light variability data are subject of a later talk. It is immediately obvious that a good correlation exists between polarization and shell indications deduced by other methods. In fact, the stars with the strongest shell characteristics are also highly polarized.

Figure 1 shows the distribution of polarized and unpolarized stars in the color-magnitude diagram of NGC 2264. No clear correlation between the incidence of polarization and luminosity and color is apparent, but this might be caused by small number statistics. The fainter polarized stars (i. e. excluding W 46) all show a similar wavelength dependence of polarization peaking in the blue, as shown in Figure 2. This can be interpreted as being caused by small dust particles in circumstellar shells. W 46, on the other hand, is unusual in several respects. It is the brightest A star in the cluster which might indicate that any shell absorption in

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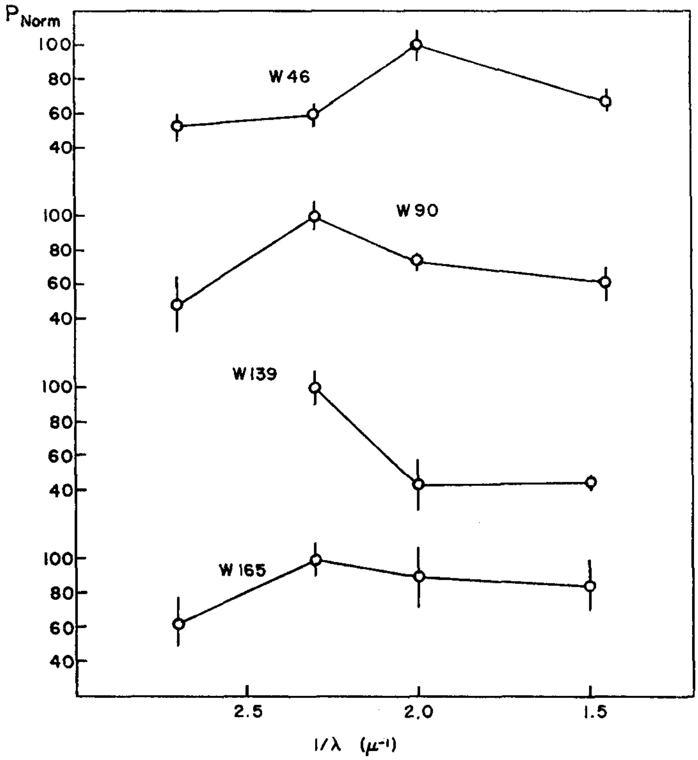

Fig. 2: Wavelength dependence of measured polarization.

the visual should be small, the opposite as previously suggested for the fainter shell stars. The wavelength dependence of polarization in W 46 is different from that of the other stars since it peaks in the visual. In fact, W 46 is very unusual in other respects too, e. g. the infrared measurements also predict a thick shell, while the gravity determination of $\log g = 3.6$ predicts very little shell absorption in the visual. If W 46 is really unusual, it should be interpreted separately. Figure 1 then confirms the results that the fainter stars in NGC 2264 are surrounded by extensive shells resulting in heavy visual absorption.

We conclude that the polarization measurements confirm the existence of shells around several pre-main sequence stars. The fact that no new shell stars of spectral types A/F were found by this method reinforces the view that most of the brighter pre-main sequence A/F stars in NGC 2264 are not surrounded by *extensive* shells. Consequently, not all the scatter in the color-magnitude diagram can be attributed so shell absorption and an age spread of about 1 to 3×10^6 years is indicated on the basis of classical evolutionary tracks.

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SERKOWSKI: Can the observed wavelength dependence of polarization be explained by the electron scattering and hydrogen absorption?

HARDORP: I don't know. However, dust must be in the shells because of the large IR-excess, and if dust particles are the explanation for the polarization as well, the particle size must be of the order of 4000 Å.

GEYER: Is the membership of these stars safe? Are there radial velocity measurements or proper motion determinations?

HARDORP: Yes, there are. According to the radial velocity and proper motion studies the stars discussed are members or probable members.

BEHR: What is known about the foreground (interstellar) polarization in the region of the cluster and what is the amount of interstellar reddening?

HARDORP: There are not many foreground stars; the reddening of the stars in the cluster is some hundredths of a magnitude.

Microwave Emission from Stars

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I. Introduction

During the past several years, the radio astronomical detection of a large number of complex organic and inorganic molecules has led to an entirely new concept of the chemical composition, kinematics and excitation of the interstellar medium. The microwave molecular transitions detected thus far fall into two natural categories: 1. „normal" (i. e. nearly LTE) emission and absorption lines, and 2. anomalous or „masered" emission lines. The first category includes molecules found in both high and low excitation regions whose intensity, linewidth and other characteristics may be described in terms of a physically realistic excitation temperature. Nearly all of the known microwave lines fall into this category. Typically, molecular lines of this type are found in HII regions, dark nebulae and, occasionally, extended circumstellar shells. Only two molecules populate the second category: OH and H_2O. Emission from OH lambda doublet transitions in several rotational states and from the 6_{16}—5_{23} rotational transition of H_2O exhibits many strange characteristics: tremendous intensity, narrow linewidth, non LTE distribution of hyperfine intensities, linear and circular polarization, and rapid variability. OH and H_2O emission originates from extremely localized regions, often as small as a few A.U. in diameter, in or near some HII regions and some cool, late type stars. The behavior of OH and H_2O emission lines is best explained by assuming that the microwave radiation is amplified by some narrow band non-linear process in the sources.

OH and H_2O lines, alone, exhibit masered emission with characteristics that are remarkably similar and usually originate from the same localized regions. That two chemically related molecules should behave in this way is, itself, puzzling; but, when the fact that many of the sources of masered emission are late type stars is also considered, the problem takes on even more interest and challenge. In the following sections, I will attempt to summarize the observations of masered emission from stars and, hopefully, outline some basic conclusions that can be drawn from the data. It should be obvious that this problem represents the proverbial „two edged sword". The association of masered microwave emission with well studied objects like stars allows us to use the information gathered by conventional optical observations to attack the general masering problem and, conversely, the radio observations may be used to obtain information about a star not readily accessable optically such as the mass loss rate or the physical conditions in a circumstellar shell.

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