A MICROCOMPUTER-CONTROLLED FABRY-PÉROT SPECTROMETER FOR THE VISIBLE*

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A portable and microcomputer-controlled Fabry-Pérot spectrometer used to obtain photoelectric line profiles of galactic and extragalactic H II regions is described. The étalon is of the piezoelectrically scanned type and is servo-stabilized by a capacitance micrometry technique (Hicks, Reay, and Scadden 1974). The detector is a photomultiplier with a GaAs photocathode. Control of the scanning and data acquisition are achieved with a HP-85 microcomputer.

Spectral resolution is about 15,000 at Hα. The optical configuration of the collimator can be modified to adapt with an f/8 or f/15 telescope aperture ratio. The maximum field of view of the spectrometer on the Mount Megantic 1.60-meter telescope is 0.8 arc minute at f/8. Examples of observations are presented and briefly discussed.

Key words: instruments—Fabry-Pérot interferometry—H II regions

I. Introduction

The spectroscopic study of extended faint objects, such as supernova remnants, or galactic and extragalactic H II regions, requires the optimization of every component of the optical system and detector. For the observer desiring to establish the velocity field of extended objects (θ ≳ 1″) with a high S/N ratio, using a few spectral lines, the use of a scanning Fabry-Pérot (F-P) interferometer is an excellent approach, due to the high-luminosity-resolution product of this type of spectrometer; Atherton et al. (1982) have discussed the performance of a F-P interferometer compared to that of a slit spectrograph.

The usual configuration of a F-P spectrometer uses a single detector on-axis to select the central interference fringe of an emission line from a region of the sky delimited by an entrance and/or exit diaphragm. Meaburn (1976) has reviewed several configurations of F-P spectrometers and Roesler (1974) discusses the many constraints of the optical layout. To achieve wavelength scanning, it has been customary, until recently, to produce a variation of the refraction index in the étalon gap by changing the gas pressure. Such systems were developed by Jacquinot (1954, 1960), Davies, Ring, and Selby (1964), and Cruvellier (1967). Several similar instruments have been built; these have been used to study galactic H II regions (Smith and Weedman 1970a,b; Bohuski 1973; Caplan 1972; Balick, Gull, and Smith 1980; Balick, Boeshar, and Gull 1980; Hipplelein and Münch 1981), and extragalactic H II regions (Smith and Weedman 1970b; Melnick 1977, 1978), planetary nebulae (Bohuski, Smith, and Weedman 1970; Smith and Weedman 1972), supernova remnants (Reynolds 1976; Münch and Taylor 1974), and the interstellar diffuse Hα emission (Reynolds 1983). Multiple-étalon systems such as PEPSIOS (Vaughan 1967) have played a crucial role in providing the selectivity to obtain stellar or interstellar absorption-line profiles.

The F-P plate separation can be changed by the variation of a voltage applied to piezoelectric stacks inserted in the separators on the periphery of the mirrors. Such scanning F-P spectrometers have been in use since the early seventies. They have been pioneered by the Berkeley group (Holtz, Geballe, and Rank 1971; Geballe and Rank 1973; Treffers 1981), by Nadeau (1981), and by Persson, Geballe and Baas (1982). A most important development has been the addition of a method of active stabilization to correct moderate misalignments in piezoelectrically scanned etalons (Hick et al. 1974; Smith et al. 1976). Such an interferometer based on Hicks' design is commercialized by Queensgate Instruments, Ltd. of London. The Hicks/Queensgate instrument coupled to photon-counting cameras is now used by workers at the Marseille Observatory (Boulesteix et al. 1983), the Anglo-Australian Telescope (Atherton et al. 1982), and the Canada-France-Hawaii Telescope (Mauna Kea, Hawaii). Geballe and his co-workers also used such a system for IR observations at the UKIRT telescope (Mauna Kea, Hawaii) while Geballe and Persson are working on a similar system for the Palomar Observatory. In this paper, we describe a portable scanning F-P spectrometer for the visible using a Queensgate interferometer.

II. Description of the Spectrometer

The spectrometer is attached to the telescope with its specialized guiding head (Fig. 1). This one has an off-axis

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ISIT TV guiding system and various other functions such as a calibration unit, a viewing eyepiece, a slide of entrance diaphragms of different sizes, and a tiltable interference filter drawer. We have several filters centered on the main nebular lines and their redshifted wavelengths. The filters for Hα or [N II] 654.8 nm and 658.4 nm should be narrow-band and selective enough (3 or 4 periods) in order to reject the other unwanted bright nebular lines. The optics for the calibration unit includes simple optics in order to reproduce the primary mirror lit by the calibration lamp.

The Fabry-Pérot etalon and its servo-stabilization unit (CS 100) have been built by Queensgate Instruments, Ltd. The etalon has an effective diameter of 50 mm and a variable spacing with a nominal value of 348 ± 5 μm. The planeness of the mirrors is of the order of λ/50 at 546.1 nm. The reflectivity is 82 ± 1% over a range of 100 nm centered at 650 nm (effective finesse ~ 14.1). We observe Hα at order ~ 1060; the free spectral range is Δλ = 0.620 nm (Δν = 283 km s⁻¹) and the FWHM of the Airy peak corresponds to δλ = 0.046 nm (δν = 21 km s⁻¹) at Hα. These interferometer specifications were chosen in order to provide an intermediate bandwidth which admits a reasonable flux and a large enough free spectral range to scan the velocity field of most galactic H II regions and of many late-type galaxies, while avoiding the superposition of the night sky OH lines on the Hα line.

The etalon is the result of a design by Hicks and his collaborators at the Imperial College of Sciences and Technology (Hicks et al. 1974). The stabilization of the etalon is achieved by capacitance micrometry; this technique and its advantage have been discussed in several of the papers mentioned earlier. We have also used our etalon as part of a Fabry-Pérot camera (Roy et al. 1982; Joncas and Roy 1984). The controller and servo-stabilizer of the interferometer should be turned on at least three hours before the beginning of the observations in order to avoid the slight drifts due to initial electronic noise. To assure the greatest stability, we flush the etalon gap with dry N₂ during the observation in order to insure against humidity-variation induced drifts. The CS 100 is normally left with power on for the whole length of the observing run. We have operated the Queensgate interferometer in the scanning mode at temperature as low as −27° C without any problem.

The collimating lens, a commercial 200 mm f/3.5 Vivitar lens, forms an image of the primary mirror in the plane of the etalon. A field lens and a focal ratio converter lens can be introduced ahead of the collimator to adapt an f/8 or f/15 aperture ratio. An 85-mm lens images the interference rings on an exit diaphragm which selects the central fringe only; this diaphragm is not really needed in our system but acts as a screen against
parasitic light. A Fabry lens forms an image of the primary mirror on the photocathode of a GaAs photomultiplier (RCA C31034) cooled to dry-ice temperature.

The interferometer operates as a scanning monochromator sequentially sampling spectral elements, using an on-axis isolating aperture; the size of this aperture must satisfy the Jacquinot criterion $\theta^2/2 < R^{-1}$, where $R$ is the resolving power and $\theta$ is the angular radius of the diaphragm; on a 1.60-meter $f/8$ telescope this aperture corresponds to $\leq 0.8$ arc minute. A typical scan has up to 128 points and covers close to two successive orders of interference. The typical integration time varies between 0.1 to 2 seconds at each step, depending on the surface brightness of the object and on the sky conditions. Because of the narrow bandpass and of the low brightness of the sky in red, we can observe with a full moon.

III. Control and Data Acquisition

For data acquisition, real-time display of the scans on the CRT, and control of the interferometer via its CS100, a program has been written emphasizing an interactive approach. Our choice of a HP-85 microcomputer was based on several constraints, involving the portability and reliability of the components. This microcomputer has many integrated peripherals such as a CRT, a thermal printer and a data cartridge recording unit. In addition, its I/O ports accept the standard interfaces and its I/O ROM makes interfacing to peripheral devices easy.

The servo-stabilization unit (CS 100) possesses a parallel interface (TTL compatible) and is linked to the HP-85 through a GPIO interface, while the photon counting unit is connected via a HP-IB (IEEE 488) interface (Fig. 2). The complete program for the control, the display, and the data acquisition has more than 500 BASIC statements, which use about 15 K bytes of the computer memory. This program also allows the observer to establish the parameters specifying the type of data acquisition and display format as well as initial position and stepping values for the étalon. Data storage is on digital cartridge of 217 K bytes capacity with 42 files of five registers each, allowing the recording of 210 profiles. The data are later transferred via MODEM to the disk space of a large computer for processing.

IV. Data Reduction

Having undertaken an observing program to explore the velocity dispersion in extragalactic H II regions, we have paid a lot of attention to every factor that may contribute to the instrumental and physical broadening of the observed profile. This section discusses these particular aspects in the context of sources with angular size smaller than the entrance aperture.

There are three main sources of broadening. First, the instrument modifies the width of the true line profile of the source. Fortunately, instrumental broadening is easily evaluated. Then, there is the thermal broadening which requires a certain knowledge of the kinetic temperature in the source. Finally, there is the “turbulence” of the gas. This final product of our data reduction includes everything but instrumental and thermal broadening. Therefore, turbulence remains a broadly defined parameter. It includes small- and large-scale turbulence, expansion of isolated cells, rotation, relative motion of different parts of the extragalactic H II regions, etc.

To obtain the turbulence, we convolve the actual instrumental profile with a thermal profile characteristic of the temperature in the H II region and with a turbulence profile; the last two profiles are Gaussian. The instrumental function is established by observing a very narrow line of about the same wavelength as Hα (656.3 nm); a laser line or a line from a heavy ion such as the emission line of Ne 659.5 nm have been used. When the width of the convolved profile equals the width of the observed profile, the turbulence profile used in the convolution is characteristic of the velocity dispersion in the gas. If the velocities in the gas follow a Maxwell-Boltzmann distribution, the e-folding width of the turbulence profile corresponds to the most probable velocity. Fitting programs use the algorithms of Bevington (1969). Because the overall widths of the convolved and observed profiles are assumed to be Gaussian, profiles with
very high S/N ratio (e.g., Fig. 3) may have peak points somewhat off the fitted curve; the observed profiles are slightly more peaked because the instrumental profile is characteristic of an Airy function.

There are not only the reflectivity finesse, the parallelism, or the defects of the interferometer which modify the instrumental profile, but also the illumination and the size of the entrance diaphragm (Flynn 1966). The surface brightness of extended sources in the sky is generally nonuniform. The optical layout of our spectrometer is such that the luminosity profile of the entrance diaphragm does not alter by much the instrumental profile. Moreover, the extragalactic H II regions of our program have angular diameters smaller than the entrance diaphragm projected on the sky; consequently, the instrumental profile used for convolution is the one corresponding closely to a diaphragm of the same angular size as the H II region observed. The issue of extragalactic H II region diameters has been discussed in depth by Kennicutt (1978) who measured angular isophotal Hα diameters for a large number of the largest and brightest extragalactic H II regions in nearby galaxies. We are using his values of angular diameters defined by the solid angle enclosing all isophotes brighter than \( \geq 5 \times 10^{-16} \text{ ergs cm}^{-2} \text{ arc sec}^{-2} \).

V. Observations

This section presents examples of the observations obtained with the F-P spectrometer and of some of the physical information that can be extracted from nebular line profiles.

In order to check the reliability of our instrument, we studied the kinematics of the Orion nebula by measuring the radial velocity of the ionized gas at several points of the nebula. Figure 3 shows two of 25 line profiles observed at Hα, He 587.6 nm, and [N II] 658.4 nm which have been compared to those taken by Balick, Gull, and Smith (1980). We measured line profiles at the same positions as in the observations of Balick et al. However, the diaphragm used was 30 arc sec in diameter compared to 120 arc sec for Balick et al. Seven of our twelve Hα profiles have \( V_{LSR} \) being on average 2.3 km s\(^{-1}\) more negative, while five are 1.5 km s\(^{-1}\) more positive than the velocities of Balick et al.; of the six He 587.6 nm profiles, five are on average 1.3 km s\(^{-1}\) more negative; the last profile is 5.6 km s\(^{-1}\) more positive. Taking into account the different aperture sizes of the two experiments, the agreement is excellent. Our data have a bias toward slightly smaller velocities, a difference which can be explained by uncertainties in the calibration.

The high resolving power of the F-P interferometer can be used to look for line splitting, easily seen in some planetary nebulae. The wavelength difference in the two components of the split line gives directly the expansion velocity. Figure 4 shows the [N II] 658.4 nm line of the planetary nebula NGC2392. Although the signal-to-noise ratio is not very high (300 counts at maximum), it is sufficient to show two components of the line separated by about 50 km s\(^{-1}\), which can be explained as a shell expanding at about 25 km s\(^{-1}\) from the central star.

Measurements of Hα profiles have also been made in
two of the brightest filaments on opposite sides of the old supernova remnants VRO 42.05.01. This object is very faint; therefore, the values of $V_{\text{LSR}}$ and velocity dispersion (Table I) have larger uncertainties. Our velocities agree with those of Lozinskaya (1979) who observed values of $|V_{\text{LSR}}| \leq 30$ km s$^{-1}$ for the five brightest filaments.

Figures 5, 6, and 7 show Hα line profiles of three extragalactic H II regions. The red asymmetry of the Hα profile of the brightest giant H II region in NGC 4631 is peculiar. Curiously, of all the observed profiles of extragalactic H II regions, it is the only line profile showing such an asymmetry (Fig. 7). This large H II region coincides in position with the strongest of the radio continuum triple source found in this galaxy (de Bruyn 1977; Duric, Crane, and Seaquist 1982). This is the only H II region that we have observed in an edge-on galaxy. An explanation for the broad asymmetrical Hα profile is that we are observing more than one H II region along the line of sight having different radial velocities. Such a profile could also be produced by expansion of this large region; emission from the far side receding material of the H II region suffers more extinction than the near side approaching material.

In each of these observations, line profiles from a calibration lamp were obtained before and after the observation of the object. The largest drifts measured in the separation of the plates of the F-P amounted to 2.7 nm. Such drift introduces an error $< 2$ km s$^{-1}$ in radial velocity.

The arrival on the market of reliable high-quantum-efficiency array detectors is likely to make a spectrometer such as ours obsolete, at least for the purpose of surface photometry or of velocity mapping of extended sources. However, such a spectrometer will continue to be an efficient tool when information is needed for several points spread over a large area such as in the investigation of supernova remnants, of the galactic diffuse emission, or of the brightest extragalactic H II regions in nearby galaxies. Indeed the massive effort in data reduction required for array detectors is sometimes a major impediment; many projects have requirements in spatial resolution which can be met by a spectrometer. Finally, another powerful application is the use of a F-P spectrometer as a nebular photometer because it provides simultaneous measurement of the continuum and of the

![Fig. 4—[Nii] 658.4 nm line profile of the planetary nebula NGC 2392. The entrance diaphragm was one arc min in diameter. Wings of the other orders of interference appear at left and right.](image)

![Table I](image)

<table>
<thead>
<tr>
<th>OBJECT</th>
<th>POSITION</th>
<th>TEMPERATURE</th>
<th>$V_{\text{turb}}$</th>
<th>RADIAL VEL</th>
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<td></td>
<td>$\alpha$ (1950.0) $\delta$</td>
<td>K</td>
<td>km s$^{-1}$</td>
<td>km s$^{-1}$</td>
</tr>
<tr>
<td>M42 (θ$^1$C)</td>
<td>5$^h$32$^m$49$^s$; -5$^0$25$'$16&quot;</td>
<td>10 000</td>
<td>16.0 ± 0.7</td>
<td>1.0 ± 0.7 **</td>
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<tr>
<td>M42</td>
<td>5$^h$32$^m$49$^s$; -5$^0$27$'$16&quot;</td>
<td>10 000</td>
<td>17.0 ± 0.7</td>
<td>-4.0 ± 0.7 **</td>
</tr>
<tr>
<td>VRO 42.05.01</td>
<td>5$^h$22$^m$35.8$^s$; 43$^0$07$'$40&quot;</td>
<td>-</td>
<td>-</td>
<td>-20.0 ± 4.0 **</td>
</tr>
<tr>
<td>VRO 42.05.01</td>
<td>5$^h$23$^m$42.8$^s$; 42$^0$42'04&quot;</td>
<td>10 000</td>
<td>20.0 ± 4.0</td>
<td>-21.5 ± 2.7 **</td>
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<tr>
<td>N2366-I</td>
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<td>15 600$^+$</td>
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<td>94.0 ± 1.5</td>
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<tr>
<td>N4395-I</td>
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<td>23.0 ± 1.5</td>
<td>285.0 ± 1.5</td>
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<tr>
<td>N4631-I</td>
<td>12$^h$39$^m$45$^s$; 32$^0$49'00&quot;</td>
<td>-</td>
<td>-</td>
<td>673.0 ± 1.0</td>
</tr>
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</table>

(*) The rms velocity of turbulence is $v_{\text{turb}} / \sqrt{2}$.

(**) LSR radial velocity; other are heliocentric.

(†) Temperature measured by Kennicutt, Balick and Heckman (1980).
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Fig. 5—Hα line profile of the largest H II region in the galaxy NGC 2366. The zero point of the wavelength scale corresponds to 656.15 nm. See Table I.

Fig. 6—Hα line profile of the largest H II region in NGC 4395. The zero point of the wavelength scale corresponds to 656.58 nm. See Table I.

Fig. 7—Hα line profile of the largest H II region in the edge-on spiral galaxy NGC 4631. The profile is very broad and has a conspicuous red asymmetry. A Gaussian fit is shown for reference. The zero point of the wavelength scale corresponds to 657.43 nm. See Table I.

We thank R. Bisson whose assistance was crucial in the interfacing of the peripherals with the microcomputer. The construction of the instrument was done mainly by G. Pigeon and A. Bouffard. C. Beaulieu and G. Plante helped in the preparation of the manuscript.

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