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Fabry-Perot spectroscopy in space science

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Abstract. The paper describes use of Fabry-Perot (FP) systems in spectroscopic studies of astronomy and earth's upper atmosphere. Factors influencing the resolution, luminosity and instrumental line shape of FP spectrometer are discussed and the need for their optimization is emphasised, if desired luminosity gain is to be realised in practice. Use of FP as imaging spectrometer, scanning spectrometer and as a narrow band filter are illustrated. Tandem FP systems are briefly dealt with.

Keywords. Fabry-Perot; interference spectroscopy; high resolution spectroscopy.

1. Introduction

A significant advancement occurred in the understanding of spectrometers when Jacquinot (1954) made a comparative study of different systems employing respectively prism, grating or an interference device like Fabry-Perot etalon for dispersing wavelengths. He evaluated the spectrometers on the criterion of the product:

$$L \times R = \text{flux collecting power} \times \text{resolving power}$$

flux collecting power being defined through a parameter known as "Etendue" or "luminosity", also introduced by the same author. He concluded that the interference spectrometers like Fabry-Perot (FP) are greatly superior in this respect to prism or grating instruments. Their luminosity advantage, which is now commonly referred to as "Jacquinot advantage" is, however, not peculiar only to FP systems, but is a common attribute of interference spectrometers with circular symmetry (*e.g.* Michelson two-beam fourier transform spectrometers). It is also possible to have a spectrometer system for which the $L \times R$ product exceeds the value 2π attained by the above mentioned interference spectrometers, by employing field widening techniques, first introduced by Connes (1956, 1958; see also Baker 1977). In this review, we limit our considerations to the techniques for FP spectroscopy with reference to their use in different areas of space science. The $L \times R$ advantage of interference spectrometers is concisely summarised in figure 1. It should be borne in mind that this advantage applies only in situations where the image of the source overfills the entrance aperture of the spectrometer. For example, for stellar sources which are essentially point objects, this advantage may not apply. However, the atmospheric seeing scintillations sufficiently smear out a stellar image so that at very high resolutions ($\sim 10^5$–10^6) FP spectrometers have flux collecting advantage over grating spectrometers even for stellar work (Meaburn 1976). In general, however, the most potential area of application of FP spectroscopy is to the observations on extended objects.

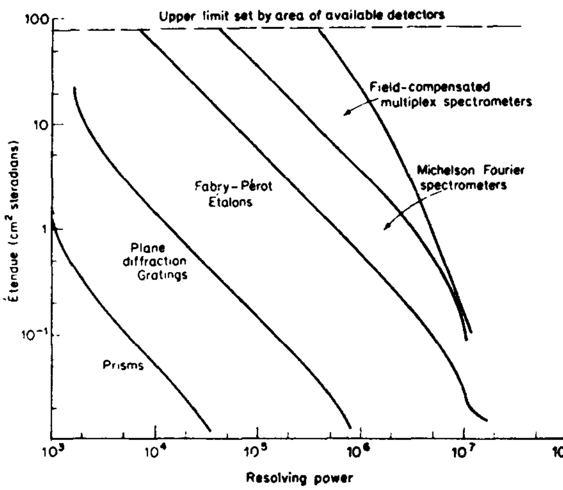


Figure 1. Etendue (*i.e.* luminosity) *vs* resolving power for different spectrometer systems. (from James and Sternberg 1966).

2. Fabry-Perot spectrometer

A FP spectrometer is basically a pair of high quality fused silica plates, each coated with a high reflecting layer and kept accurately parallel with some spacing t between them. With a fixed separator between the plates, the device is usually referred to as FP etalon. Multiple reflections in the gap produce circular fringes of high contrast and sharpness, when the device is illuminated by extended monochromatic source. Fringes can be focussed using a camera lens at the focal plane. The reflecting layers in the FP spectrometer for practical use are now-a-days invariably of multilayer dielectric type rather than metal film like silver coating, in order to avoid severe transmission loss at high finesse, *i.e.* high reflectivity (figure 2) (Title 1970).

An important aspect of FP fringes is the fact that each point on a fringe is uniquely connected to a specific direction of incidence. Thus the interferogram at the focal plane of camera lens has both spatial and spectral resolution of an extended source. This property is of considerable significance to its astronomical applications. A major limitation of FP fringes is their rather severely limited free spectral range (FSR) $= \lambda^2/2t$; over which information can be obtained without an order overlap. A parameter of FP which is of prime importance is its "finesse coefficient" N defined as the ratio of FSR to the instrument width. Instrument width is defined as the width at half power point of the fringes produced by FP for an ideally monochromatic source. Finesse coefficient gives essentially, the number of resolved spectral elements within one FSR. The instrumental width of FP is a convolution of several independent line broadening functions (Chabbal 1958); *viz* broadening due to (a) plate reflectivity not being 100% (Airy function); (b) plate deflects, including plate curvature and microtopographical polishing errors; (c) departure from strict parallelism of plates.

The ratio of FSR to the width of each of the above broadening functions defines a corresponding coefficient of finesse. Thus, we have reflective finesse N_R, defect finesse N_D and misalignment finesse N_P. Width of the function resulting from convolution of

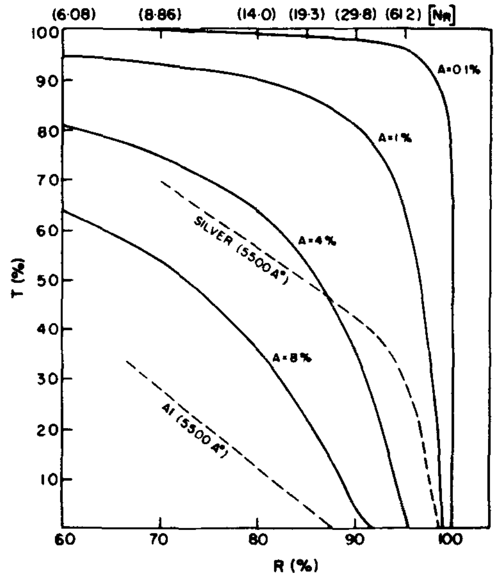


Figure 2. Transmission *vs* reflectivity of FP etalon for reflecting layers of different absorption values.

the above three functions exceeds that of any individual function. Hence the overall instrumental finesse N will be less than N_R, N_D or N_P (approximately $N^{-2} = N_R^{-2} + N_D^{-2} + N_P^{-2}$). As we shall see, optimization of the relative N_R, N_D and N_P values is of great importance in efficient use of FP spectrometer. Analytical forms of the broadening functions are discussed in detail by Chabbal (1958) and Hernandez (1966; 1970; 1974) and hence only a summary is given here.

(i) Broadening associated with finite reflectivity is the well-known Airy function $N_R = \pi\sqrt{R}/(1-R)$.
(ii) Broadening associated with plate curvature is a rectangular function with full width $(2 \times \text{FSR})/D$; giving associated finesse $N_D = D/2$. Here $D = \lambda/x$ where x is the Sagitta of curvature.
(iii) Broadening associated with microtopographic polishing errors (assumed to have gaussian distribution) is a gaussian function. Associated finesse coefficient is $N_{D'} = D'/4{\cdot}7$. $D' = \lambda/x'$; where x' = rms departure of plate surface from an ideal plane.
(iv) Broadening associated with misalignment is a cosine function, the associated finesse coefficient is $N_P = P/\sqrt{3}$. $P = \lambda/X$, where X = change in separation between plates measured over diametrically opposite ends in the direction of wedge.

For detailed convolution properties of the above functions see Chabbal (1958).

With modern vacuum evaporated multilayer dielectric coatings, one can reach N_R values up to 300 without encountering serious transmission loss due to absorption. Modern developments in polishing techniques permit achieving plate figure $\sim \lambda/200$ (Leistner 1976) which give $N_D \sim 50$. But control of parallelism to the accuracy matching $\lambda/200$ is a difficult problem; and hence N_P becomes usually the limiting finesse. The problem of attaining high accuracy in parallelism was first attacked by Ramsay (1962, 1966) who used Brewster's fringes as auxilliary signal for servo-control.

Recently Hicks *et al* (1974) developed a servo-controlled system using capacitance micrometry which permits maintaining parallelism of the order of $\lambda/200$. In situations where circumstances are not so demanding, optically contacted FP etalons (Smart and Ramsay 1964) which are now commercially available and comparatively inexpensive, can be used with advantage (Sahu *et al* 1983). Their use permits highly stable working values of finesse up to $\sim$ 12–15; whereas etalons with free spacer, using adjustments with pressure points in a conventional way (Hindle *et al* 1967) at the best attain over all finesse $N \sim 7$ and maintainance of alignment is difficult when the spectrometer is used in a movable configuration such as Cassegrain focus of a telescope. With servo-control techniques of Hicks *et al* (1974) values of N up to 60 have been attained and can be maintained with high stability.

3. FP etalon as an imaging spectrometer

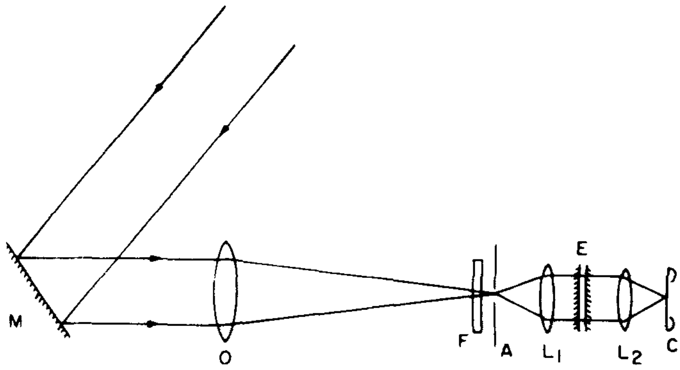
As emphasized earlier, each point on FP fringe corresponds to a definite direction of incidence flux and hence to a definite location on the object under study. The interferogram gives, therefore, an imaging spectra of the source. Figure 3(a) shows a typical application: set up used for taking interferogram of solar corona during total solar eclipse. Figure 3(b) shows coronal interferogram acquired in 5303 Å line of Fe XIV during the total solar eclipse of 1980 (India). Microphotometric study of fringe positions and fringe widths on the interferogram gives temperature and velocity field mapping of the solar corona (Desai and Chandrasekhar 1983). Splitting or bow shaping of the fringes locate positions of rather strong differential gas velocities (Chandrasekhar *et al* 1981).

FP interferograms have also been very useful in observations on gaseous emission nebulae, to study their velocity fields and turbulence structures (Deharveng 1973). Double-humped profiles signifying the expanding shells are frequently observed in planetary nebulae (Sahu *et al* 1983). Often one also observes finer structures in the profile, implying finer velocity structures or multiple shells; and asymmetric line profiles which could possibly be due to extinction by dust (redward shifted receding front suffering more extinction than the violet-advancing front, resulting in steepening of redward wing).

Relative line intensities can also be used to infer elemental abundances in the shell matter.

One specific difficulty encountered in interpreting such interferograms, particularly those of gaseous diffuse nebulae, has been the existence of sharp intensity gradients over the source. In general, distortions due to these cannot be unambiguously separated from those resulting from velocity gradient. To circumvent this problem, a device known as "insect eye camera" first introduced by Courtes *et al* (1966, 1968) is frequently used. In this case, the FP etalon is placed in telecentric position at the focus of telescope instead of being placed in the collimated beam after the focus in the conventional way. The image field is spatially resolved by an array of small camera lenses called "insect eye" placed immediately after FP; each producing a fringe pattern. The cone angle of the incident flux at the FP is so adjusted as to cover just over one order. Array of interferograms thus acquired now gives an array of velocity pictures—each corresponding to one spatial region of the source defined by location of corresponding insect eye lens. Intensity variations over the object have now no effect on fringe

(a)



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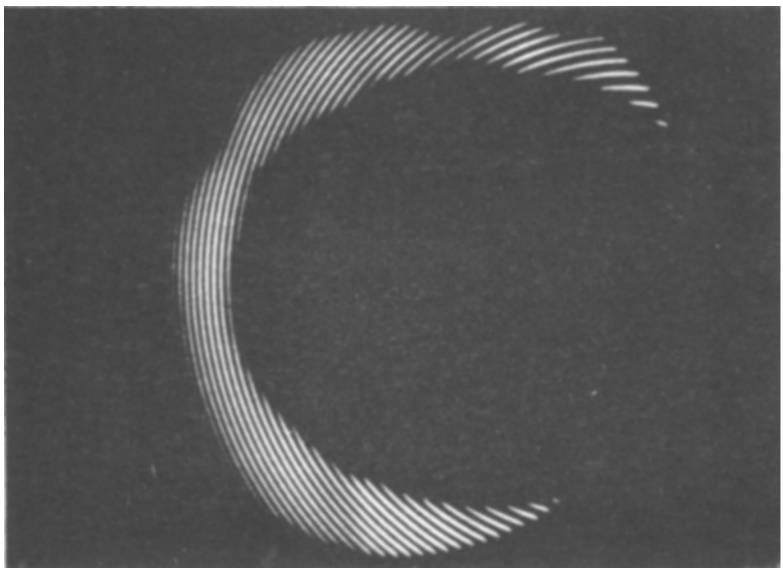


Figure 3(a). Schematic setup for coronal interferogram. Objective O forms the image of sun and corona at the aperture A. Extended field at A is collimated by L_1 and imaged by L_2 on the camera film. (**b**) Interferogram of solar corona in 5303 Å line (solar eclipse; Gadag, India 1980).

diameters, but there is considerable sacrifice of the spatial resolution. Figure 4 illustrates the optical arrangement.

Low order FP etalons with high value of effective finesse are very efficient tunable narrow band filters, when used in conjunction with interference filters. Solid etalons (made as thin wafers of fused silica $\sim$ 100 μ thickness) have been used as 0·7 A filters for Hα imaging of Sun on Skylab telescopes (Markey and Austin 1977). For a summary on tunable Fabry-Perot see Atherton *et al* (1981). Using servo-controlled parallelism, Atherton *et al* (1982) have designed a spectrometer system named TAURUS which when used with a large aperture telescope (4 m) attain a seeing limited resolution ($\sim$ arc sec) over a field of 9 arc min diameter, with a spectral resolution of 10^5. The spectrometer uses the image photon counting system developed by Boksenberg (1972) as a two-dimensional detector. This instrument has been used very successfully to obtain

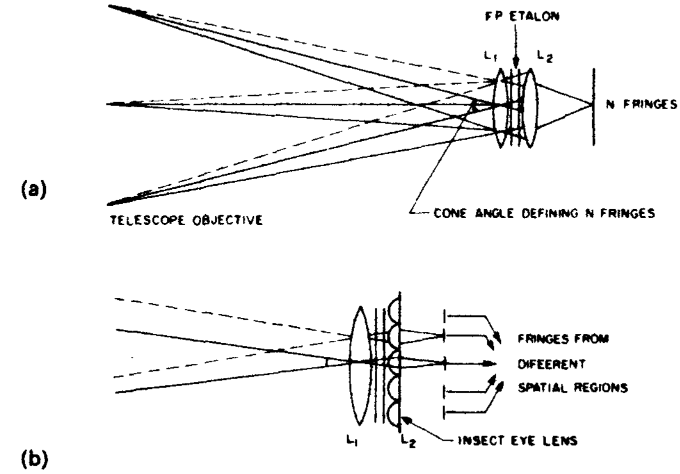


Figure 4(a). Telecentric use of Fabry-Perot. N gives number of fringes in the cone angle. **(b)** use of insect-eye lens.

velocity field maps on planetary nebulae with extremely high spatial resolutions (Reay *et al* 1983a, b). Such kinematical studies of planetary nebulae play a key role to the understanding of the late stages of stellar evolution and their mass ejection processes resulting in the planetary nebular stage. A somewhat similar instrument, (servo-controlled polarimetric imaging FP interferometer-SPIFI) has been described by Smith *et al* (1976) and its use has been demonstrated for the study of comets and planetary atmospheres (Smith 1981).

Ramsay *et al* (1970) have described a tunable FP filter with a resolution $\sim 10^5$ and a field of view of 30 arc min, which was used for observations on solar magnetic fields with Culgoora solar magnetograph (Ramsay *et al* 1971).

4. FP etalon as a scanning spectrometer

When emphasis is not on the imaging aspect, FP etalon can be used with advantage as a wavelength scanning spectrometer by placing an exit aperture of suitable angular diameter (as subtended at the camera lens) at the focal plane of fringes. The aperture isolates the central fringe and thus allows limited wavelength band $\delta\lambda$ to reach the detector. The wavelength band transmitted is given by

$$\delta\lambda/\lambda = \theta^2/2;$$

θ being the semiangle of the cone made by the aperture at the camera lens (figure 5). For scanning over wavelengths either the geometrical separation t or the refractive index μ may be changed. The former can be done piezoelectrically, the latter is most conveniently done by changing air pressure in the etalon chamber. Problems of nonlinearity associated with piezoelectric scanning are discussed by Hernandez (1978). Sophisticated systems like TAURUS (Athorton *et al* 1982) where plate parallelism is servocontrolled often use piezoelectric scanning. However, for systems using optically contacted etalons, pressure scanning is the only way of wavelength scanning (apart

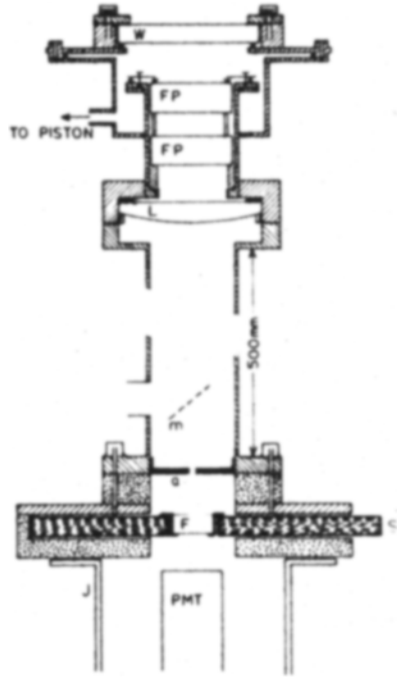


Figure 5. Schematic diagram of a pressure scanned FP spectrometer.

from tilting—which has serious disadvantages like variable instrumental line shape and nonlinearity of scanning). Since no mechanical movement is involved it is relatively easy to maintain parallelism of etalon plates. With nitrogen as the chamber gas (μ = 1·00030 at λ = 5500 and 1 atm. pressure) a wavelength change of 1·65 Å will be produced at 5500 Å by one atmosphere pressure change.

When it is required to cover a larger range of wavelengths, more refractive gases like CO_2 (μ = 1·00046); $CClF_6$ (1·0007) or SF_6 (1·00075) are used.

Application of FP spectroscopy to high resolution observations on airglow dates back to 1923 (Babcock 1923). Systematic attempts at temperature measurements from observations on line-widths were made in mid-fifties (Wark and Stone 1955; Karandikar 1956). Techniques became more refined with introduction of dielectric reflectors, photomultiplier detectors in counting mode, and better control over instrument width. Doppler widths have been measured systematically for both *E* region airglow emission at 5577 Å and *F* region emission at 6300 Å. From observations of 5577 Å right airglow widths extending over a solar cycle Hernandez (1976) showed that at 97 km altitude there is a significant modulation of temperatures by solar and magnetic activity. The linewidth and doppler shift measurements on 6300 Å airglow line from *F* region ionosphere have received considerable attention for understanding ionospheric temperatures and winds. Global measurements with FP spectrometer aboard OGO 6 (Blamont *et al* 1974) gave thermospheric temperatures which proved very useful in constructing thermosphere models. Systematic ground-based observations have been carried out from various locations ranging from near dip equator (Burnside *et al* 1981), locations approximately under appleton anomaly (Rajaraman *et al* 1979); as well as high latitude stations (Hernandez and Roble 1976a, b; 1977). Rees *et al* (1982) have recently described a FP system to be flown aboard NASA atmospheric dynamics explorer satellite, which will carry out observations on temperatures and winds on several emission lines viz. [O I] (6300) and O II (7320) which are thermospheric lines; [O I] (5577) and Na (5896, 5890) which are mesospheric lines and the auroral line [N I] (5200).

5. Optimization of finesse coefficients and deconvolution procedures

Most often, FP spectrometer is used in a rather exacting situation where available flux is a limiting factor, but the source is sufficiently extended to overfill the entrance aperture of the spectrometer. Under such circumstances, it is necessary that both flux transmittance and flux admittance are maximized. The solid angle seen by the spectrometer is defined by the angular width of the scanning aperture, which must not be made smaller than necessary. The effective transmission of the FP spectrometer depends quite sensitively on the relative values of (i) width of the line emitted by source; (ii) airy width as governed by the reflectivity (iii) etalon defect width and (iv) width of wavelength range admitted by the scanning aperture. A detailed study of the dependence of transmittance on the above factors is given by Chabbal (1958; see also Hernandez 1970). Here some important points will be summarized.

(a) Transmittance is a decreasing function of the ratio of reflective finesse N_R to the plate defect finesse N_D. On the other hand, convolution properties of analytical functions associated with N_R and N_D show that so far as resolution is concerned, it is only the smaller of the two coefficients that will be essentially a deciding factor. Hence an optimum choice from both resolution and transmittance viewpoint is to have $N_D < N_R < 1{\cdot}3N_D$. (b) The etalon transmittance also depends upon the ratio of linewidth of the source to the width of etalon function. Keeping etalon width much narrower than source linewidth results in a low transmittance, without effective improvement in resolution. Too small a value for the scanning aperture may result in loss of flux admittance for an extended source. Under most practical situations it is best to choose a scanning aperture such that the wavelength width admitted by it is equal to the width of the source line after convolution with the etalon function. Whereas what is mentioned above are only broad guidelines for optimization, for detailed considerations reference to Chabbal (1958b) is strongly recommended.

In order to obtain accurately the line profile of the source, the recorded profile has to be deconvoluted with the instrument profile. Reliability of deconvolution will depend upon the accuracy to which the instrument profile is determined; and also on signal-to-noise ratio in the recorded profile. Procedures for deconvolution have received considerable attention. Analytical aspects to the problem of retrieval of true linewidth from the observed width are discussed by Hernandez (1978, 1979, 1982). Zipoy (1979) has stressed the importance of optimum sampling; showing that both under sampling as well as over-sampling can be harmful. He also gives a detailed algorithm for deconvolution. Hays and Roble (1971) have described a deconvolution procedure suited to profiles of weak intensity and large statistical noise.

Enhancement of luminosity of FP spectrometer can be achieved by replacing central scanning aperture with a multizone analyser which allows flux from more than one fringe to be received on the detector. Such a device is particularly useful in context with airglow temperature measurements where field of view poses no problem. A ten-zone system has been described in detail by Okano *et al* (1980) and a gain flux almost by a factor of ten is reported.

6. FP Etalons in series

Due to the limited FSR, transmission in unwanted orders poses a serious problem to the application of single FP etalon when fine structures in a broad emission profile, or absorption signatures in a continuum emission are to be examined. Although the problem can be solved to some extent by using etalon with a very high effective finesse (~ 50), this needs extremely well figured plates and great care in maintainance of parallelism. Use of etalons in tandem can take care of this problem very efficiently albeit with considerable loss of transmissivity and total sacrifice of imaging property. Properties of such systems (polyetalon pressure scanned interferometric optical spectrometer PEPSIOS) have been studied in detail, particularly with respect to the transmission of parasitic light outside the transmission band. Figure 6(a) illustrates the basic scheme of the device with three etalons in vernier spacer ratio. With respect to the transmission of parasitic light, it has been shown (McNutt 1965; Stoner 1966) that the spacers in ratio of 1:0·8831:0·7444 form an optimum combination. One desirable consequence of the combination of etalons is the great improvement in the shape of the instrument profile, especially with respect to enhanced suppression of transmission in the wing as shown in figure 6(b) (Meaburn 1975).

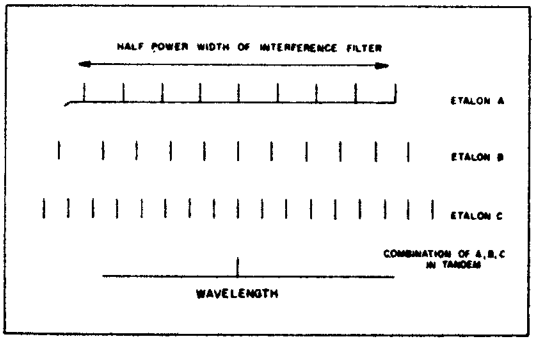
Using such 3 etalon Pepsios spectrometer, Hobbs (1969) studied stellar absorption line profiles with a resolution as high as 6×10^5. Meaburn (1972) has shown that a combination of two etalons is sufficient in less critical situations like observing broad (2 Å) emission profiles in planetary nebulae with a resolution of 0·07 Å (This would need a single etalon of finesse ~ 30; but combination of two suitable optically contacted etalons in rather relaxed condition of $N \sim 12$ suffice). Two etalon systems have also been used successfully for observing linewidth of 6300 Å airglow line during daytime (Cocks and Jacka 1979).

7. FP spectroscopy in IR astronomy:

Gaseous components of interstellar matter and interstellar clouds could be a rich source of atomic and molecular lines. There are specific advantages like reduced optical thickness of interstellar matter, in observing lines in the IR, particularly in regions of heavy obscuration like galactic centre. Such observations could be valuable in studying physical conditions and processes in interstellar matter and cloud complexes. There are about a dozen potential candidate lines including O III (51·8 μ) (already observed, Melnick *et al* 1978); S III (33·6 μ) and Ne II (12·8 μ) (probably observable from a dry high altitude location as pointed out by Vanderwal and Slingerland 1979).

FP techniques are particularly well suited for the line observations in this spectral region. Usual etalons are now replaced by wiremesh reflectors, either with fixed gap or used as tunable filters with piezoelectric scanning (Anandarao *et al* 1983). The field is very young and as yet only few successful observations are reported, major difficulty being the requirement of making observations essentially from above the atmosphere.

(a)



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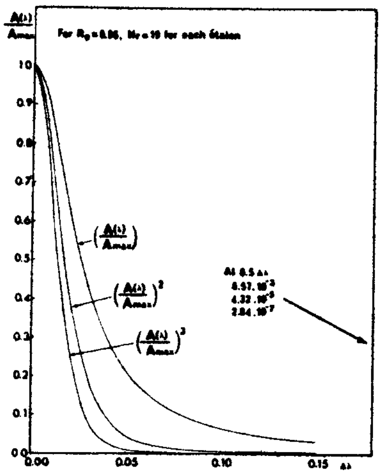

Figure 6(a). Principle of PEPSIOS. Interference filter F plus three etalons A, B and C in vernier spacer ratio in series. **(b)** Transmission profile of a single etalon compared with two and three identical etalons in series (Meaburn 1976).

8. Conclusions

The article describes the use of FP spectroscopy to high resolution observations in astronomy and atmospheric physics. The basic procedures, techniques and precautions needed are briefly dealt with. FP spectroscopy has made a tremendous progress since the days of Fabry when in 1911 he made first spectroscopic observations on Orion nebula using the device, with his colleagues Buisson and Bourget. The improved fundamental understanding of the spectrometer systems brought about by investigations by Jacquinot in 1954, and the technical progress made in art of high reflection dielectric coatings, optical figuring and servo-control methods have jointly made FP spectroscopy what it is today. With the emergence of extremely precise control of parallelism and extreme refinement in plate figure ($\sim \lambda/200$) the imaging spectrometer systems of the type introduced in recent years is sure to hold a great future promise. Very recently, Reay *et al* (1983) have reported on a stellar radial velocity meter with a sensitivity as high as $\pm 10\,\mathrm{m\,sec^{-1}}$. The authors consider its potential use for detecting stellar oscillations similar to solar oscillations (Trauger 1983).

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