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COLOR PHOTOGRAPHY IN ASTRONOMY

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Photography has been an indispensable tool in astronomy. As emulsion sensitivity increased, and as emulsions sensitized to different portions of the spectrum were introduced, new vistas opened to astrophysical investigation. In spectrographs and in combination with appropriate color filters, these emulsions have recorded detailed information about the structure of stellar systems, nebulae, and galaxies. From such plates much has been deduced concerning the colors of astronomical objects, and careful densitometry has yielded quantitative information about the relative and absolute intensities of various colors. But such negatives rarely lend themselves to the production of actual color pictures, and the probable appearance of an object in its true colors can only be synthesized in the mind of the individual investigator by careful comparison of several plates. The mental image that he forms is subjective and difficult to present in reproducible form.

Following the introduction of the first monopack color films in the mid-1930's, sporadic efforts were made at several observatories to obtain useful color photographs. The sensitivity of early materials was so low and reciprocity failure so great that little of value resulted. There is no record of any attempt to verify the validity of the colors that were recorded.

In recent years, this situation has been greatly altered; positive reversal color films are now available with sensitivity sufficient for many astronomical purposes, offering a new dimension in astronomical photography.

This new degree of freedom has been gained at a price, however—the price of added complications and the necessity for remedial measures. Most of the difficulty derives from a characteristic of photographic emulsions long familiar to astronomical photographers—reciprocity failure.

Not only is the old loss of emulsion efficiency at low light intensities encountered, but a different manifestation of this same principle arises; namely, a serious loss of color accuracy in photographs exposed for long periods. This phenomenon is not new, having bothered color photographers in other fields since the inception of color photography. But the corrections they are required to make for reciprocity failure are relatively small, since their exposures do not compare in length with those encountered in astronomy.

Efforts to remedy this difficulty are complicated by the fact that we cannot do as many commercial color photographers do, i.e., merely look at the picture and recognize that it is too red, too magenta, or too strong in any other color. Commercial color photographers can compare their results with the original subject and immediately prescribe the corrections necessary to bring the picture into balance. But we do not know what nebulae and galaxies should look like in color, for we have never seen and probably never shall see them visually in their true colors. Hence we must set up controls to advise us of all shifts of color balance, regardless of their origin. By borrowing heavily from the experience of expert commercial color photographers who are not content merely to "eyeball" their pictures, we have been able to establish successful controls that permit us to take reasonably accurate color photographs at the telescope. We do not say that these photographs reproduce the subjects with absolute fidelity, for this is not true, nor is it likely to be true in the near future because of the inherent limitations of the color process. But pictures can be taken that are as accurate as available color films permit.

To understand fully the effects of reciprocity failure in color photography, it is necessary to know the fundamental principle of monopack color film, at least in its simplest elements. Color film manufactured for camera use is composed of three separate emulsions on a single base. Each layer is sensitive to a different portion of the spectrum. In a typical film, the top emulsion is blue-sensitive. Immediately below it is a yellow filter layer to prevent blue light from reaching the underlying emulsions. Following the filter comes the green-sensitive and then the red-sensitive emulsion.

It is practically impossible to manufacture all three emulsions with identical reciprocity-failure characteristics at all light intensities and still balance the characteristics of these three emulsions in other respects essential to the success of the process. Hence, from technical as well as practical and economical considerations, the manufacturer selects emulsions whose reciprocity-failure characteristics are as similar as possible over the exposure range employed by the majority of those using the material. These are amateur and commercial photographers who require exposures between one minute and 1/500 second. In the parlance of the trade, the films are "color balanced" in that exposure range, meaning that a gray card illuminated by a source of proper color temperature will be reproduced on the film as a neutral gray image.

However, if that same light source is neutrally attenuated by a factor of several thousand and the exposure time increased appropriately, that same gray card generally will not be reproduced on the film as a neutral gray. It may predominate in blue, green, red, or any combination of two colors, depending upon which emulsions suffer the greatest reciprocity failure. This, then, is the crux of the situation facing the astronomer.

Two separate attacks have been made on the problem, one by Hoag,[1] who has investigated the effects of refrigeration of the emulsion during exposure, and one made here involving the use of correction filters. Hoag's system is particularly attractive, since it simultaneously reduces over-all loss of efficiency of the emulsion with long exposures as well as the loss of color balance. No quantitative data are yet available concerning the extent of correction of color imbalance by this system, but it is considerable, judged by photographs taken at the Naval Observatory. It is possible that residual corrections must still be made by applying color filters.

Optical and instrumental limitations make the refrigeration technique difficult to apply in all situations, and the filter system of correction is the only alternative now known.

Loss of efficiency at long exposure times varies markedly from one brand of film to another. Changes in effective speed with exposure time for the two that have been used most extensively in our work are shown in Table I.

TABLE I

EFFECTIVE SPEED VS. EXPOSURE TIME

	Exposure Index	
Exposure Time	High Speed Ektachrome	Super Anscochrome
1/100 sec	160	100
1 hour	7	11
2 hours	5	8
4 hours	3.4	7

It is clear from this tabulation that the film rated fastest by normal photographic standards is not fastest for all astronomical use.

Figure 1 demonstrates both aspects of reciprocity failure as it appears in a sample of Super Anscochrome film. At 1-second exposures the film exhibits reasonably good color balance, as indicated by the agreement of the left-hand H and D curves determined by means of a color densitometer. It is not always necessary, or even desirable, for the curves to coincide exactly. Certain technical aspects of color reproduction of everyday objects often require slight displacement of the curves relative to one another. The reproduction of monochromatic images, of emission nebulae, for instance, places different requirements upon color-film characteristics. At present, it is a point of debate whether for astronomical work the H and D curves should coincide exactly in the ideal film; the writer feels that they should.

Another factor affecting the coincidence of H and D curves obtained from samples of color film is the type of densitometry employed; more of this later.

In Figure 1, the curves at the right are the equivalent H and D curves for a sample of the same film exposed two hours to the same light source neutrally attenuated. The separation between the two groups of curves is indicative of the loss of over-all efficiency of the emulsion with prolonged exposure; the separation between the three curves at the right is indicative of the change of color balance, or accuracy, resulting from the increased exposure. In this particular sample, the red-sensitive emulsion has decreased most in efficiency, green next, and blue the least. As a result, such a film at long exposure times will record blue and green features in an image as though they were relatively much brighter than they really are.

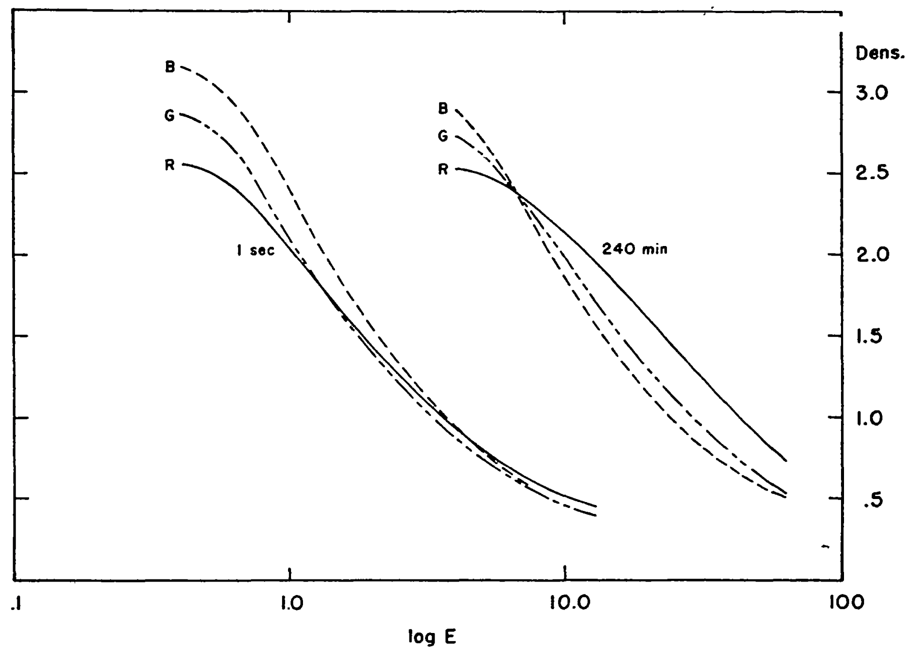

FIG. 1.—Typical effect of reciprocity failure on monopack reversible color film; both efficiency and color balance decrease with increasing exposure time.

Color-correction filters are required to remedy this situation. Filters can be applied in either of two ways: films exposed "raw" in the telescope, then processed, can be viewed through the required correction filters, and corrected duplicates can be printed onto transparency duplicating film through suitable correction filters (not necessarily the same ones required for viewing); or, correction filters can be placed before the film at the time of the original exposure to modulate the incident light. The results obtained by the two systems are significantly different, as will be pointed out later.

In all cases, it is necessary to establish an accurate means for detecting the degree of color imbalance at various exposure times for every lot of film used, in order to determine the color-correction filters required for each situation. The ideal control system should also monitor as many other sources of error as possible, and there are several.

These include such items as aging of the raw film stock, variations in processing, variations in filters, differences between successive coatings of a given brand of film, intermittency of exposure, differences in temperature and humidity, and the effect of light from the night sky. Temperature and humidity can best be monitored by moving the control equipment described below into the dome and exposing the control films simultaneously with the pictures. The effect of light from the night sky and correction of this effect are now being investigated.

The control system depends upon film samples exposed in a spot sensitometer whose light source has been accurately adjusted to the desired color temperature. The lighthouse is movable to permit perfectly neutral attenuation over a very large factor, allowing exposures from one second to the longest required at the telescope. For every film used at the telescope there must be a sensitometer control film from the same box, exposed as nearly as possible at the same time and under the same conditions as the picture film, for the same length of time through identical filters, and processed with it. This film thus suffers from the same errors that afflict the picture, and displays them in a form that permits easy and precise measurement in a color densitometer.

The density of each exposed spot on the control films is measured in three colors—red, green, and blue. When plotted against $\log E$, these values give three H and D curves, one for each layer on the film, as shown in Figure 1. From these curves are derived the data required for the selection of the correction filters for each situation.

If the corresponding picture film was exposed "raw" in the telescope, and it is desired to view it by eye, Integral Luminous or Colorimetric Densities[2] (Chapter XI) are required. If the picture is to be reproduced as a corrected duplicate, then Integral Printing Densities are needed.

In either case, application of correction filters to a processed film can achieve correction only by changing the relative densities of the three-color records present in the film. This in effect shifts the H and D curves vertically with respect to one another until they agree in some selected density range; density can be added to but not subtracted from the image. In the case of the right-hand curves of Figure 1, the blue curve can be raised into agreement with the red curve at some point, such as D = 1.5, by the application of a yellow filter whose blue density in this case is 0.50 (known as a CC 50Y filter). Similarly the green curve can be raised into agreement with the red by the application of magenta filtration whose green density is 0.35 (CC 35M). The density of any color is increased by the addition of a filter of complimentary color.

If the blue and green curves are re-plotted by displacing every point vertically by 0.50 and 0.35 density units, respectively, it will be seen that agreement with the red curve is obtained for only a limited density range. In the toe and shoulder regions serious disagreement occurs owing to the shape of the curves. One of the practical results of this is that the low densities (brightest portions of the picture) are overcorrected and will appear yellowish. There is no remedy for this situation. Hence, post-exposure correction does not yield pictures of the highest possible accuracy; the result is more accurate than no correction at all, but better results are desirable and possible.

It is obvious from the character of H and D curves that closer agreement is obtained when the curves are shifted horizontally rather than vertically with respect to one another. Horizontal shifting requires changes in relative intensities of the incident colors during exposure, not alteration of the resulting image densities. These changes can be accomplished by means of suitable filters in front of the film at the time of the original exposure. In the sample film represented by the curves of Figure 1, the blue and green emulsions are more sensitive than the red at long exposures. Filters that suitably attenuate the blue and green components of the incident beam will retard those two emulsions until they agree in speed with the red layer. Except for small losses due to surface reflections, such filters will not materially increase the exposure time, since they will not affect the red intensity which determines the required exposure time.

Inter-reflections between multiple filters suspended before the film sometimes cause ghosts around bright stars and make it highly desirable to limit the number to a single glass or gelatin sheet. This limits the accuracy of filtration possible, since mixtures of colors in the exact proportions required are not always available in a single filter. In the case of the film of Figure 1, adequate results were obtained by the use of a CC 20R (red) filter in place of the CC 25Y + CC 15M called for by the photometric data. The errors incurred are slight and can be safely corrected on the finished film by applying correction filters for viewing or duplicating. Such secondary corrective steps are usually required to correct other minor errors and all can be done at once, provided that the total of all residual errors is kept small.

Table II and Figure 2, respectively, show the color corrections required for two different brands of color film for various exposure times.

TABLE II

Color-Correction Filters Required for a Typical Sample of High Speed Ektachrome Color Film for Long Exposure Times*

Exposure Time	High Speed Ektachrome Correction Filter
1/100 second	None
1 hour	CC 10B (blue)
2 hours	CC 20B
4 hours	CC 30B

* Eastman Kodak Laboratories, private communication.

The agreement of the three H and D curves by this latter method—corrective filtration during exposure—is definitely superior to post-exposure correction. With a judicious choice of filters, the pictures as obtained with the telescope are so nearly corrected that detailed studies of colors can be made directly from the films. Even threshold images are accurate and disclose delicate differences in color. Stars of the same color temperature as the sensitometer light source will appear neutral, hotter stars will appear bluish, cooler stars reddish. For special problems, the zero point of the color system can be set at will, so that relative color temperatures of objects can be assessed with considerable speed and ease.

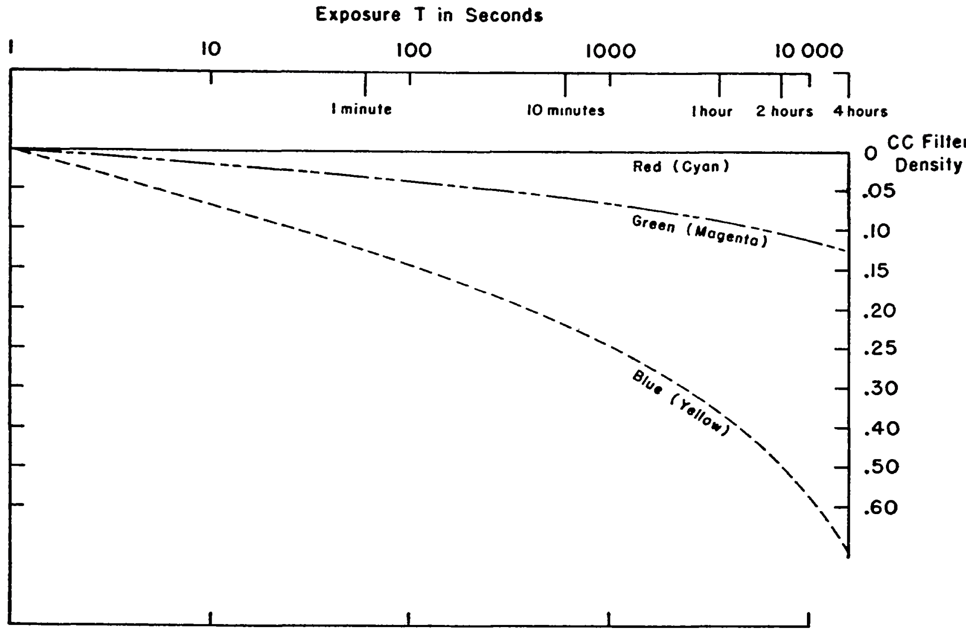

FIG. 2.—Color-correction filters required for different exposure times for one sample of Super Anscochrome film.

One precaution must be kept in mind in such work; accurate comparison of relative color usually can be made not over the entire density range of the film, but only over that portion adjacent to the density value used for determining the required correction filters. Thus, in the example of Figure 1, if we make the correction at a density of 1.5, good comparisons of color should be possible over a density range from about 0.5 to 2.0. If correction is established in the low-density portion of the H and D curves, then care must be used when comparing images of high density, and vice versa. The curves can rarely be brought into close agreement from toe to shoulder, and correction must be made for the density range most important to the problem at hand.

Whether corrections are determined for use after exposure or during exposure, sensitometer control strips must be exposed for every picture film, duplicating as exactly as possible all conditions of exposure of the picture film, even to the use of identical filters. These sensitometer strips should be processed in close association with their corresponding picture films, and should be inseparably attached to them for the duration of their useful life. The sensitometer strip is the *alter ego* of the picture film, indicating at all times the filtration necessary for correction of the picture. Since even the best dyes are not unlimited in their stability, the control strips must be consulted frequently to take into account slight changes in the color balance of the picture, which can change with age.

Limitations in over-all accuracy of color rendition of astronomical objects arise from five major sources: (1) spectral-sensitivity characteristics of the film, (2) spectral-transmittance characteristics of the processed dyes, (3) reciprocity failure and its effect on color balance, (4) variations in processing, and (5) cumulative effects of such factors as intermittency of exposure, temperature and humidity during exposure, aging of the emulsion before exposure and between exposure and processing, aging of the processed dyes, accumulated tolerances of film, filters, and so on.

The spectral sensitivity of a typical color film is shown in Figure 3. Major sensitivity is concentrated in the red, green, and blue-violet regions. The requirements for acceptable color reproduction of objects in everyday scenes with their broad color bands are less stringent than those for reproduction of the varied hues of the visible spectrum, or astronomical objects that radiate in a

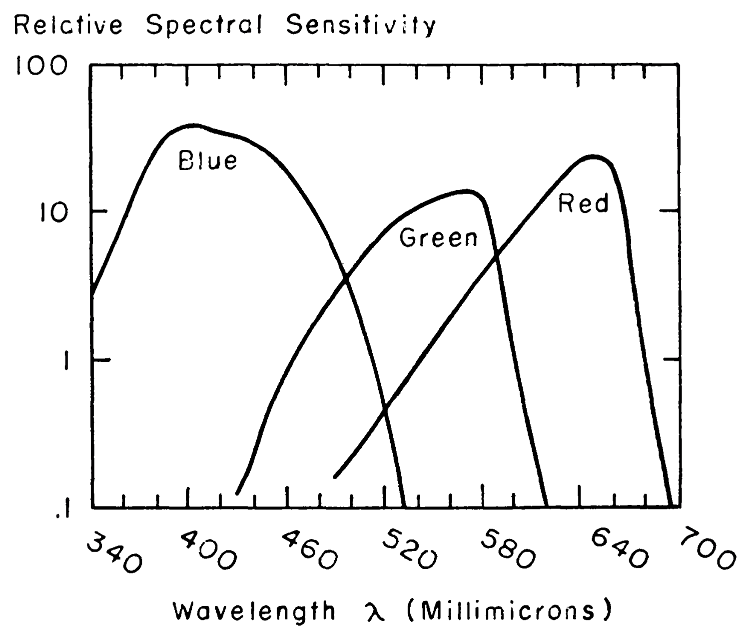

FIG. 3.—Characteristic spectral sensitivity of a monopack reversible color film.

limited number of widely separated wavelengths. Evans *et al.* (p. 396) discuss this complex problem in detail;[2] the reader is urged to consult this reference for a clear understanding of the problem.

Commercially available color films are designed for use with subjects whose colors are characterized by broad bands, and as a result are well suited to problems involving comparison of color temperature, but leave something to be desired when it comes to reproducing all the hues in the spectrum, and emission objects. Wavelengths intermediate between the three primary peaks are recorded with lower sensitivity than the primaries and with only approximate color accuracy.

This deficiency becomes conspicuous in work on emission nebulae. The only important green radiation is contributed by the N_1N_2 lines of [O III] near 5000 Å. Most films have a spectral sensitivity such that radiation of this wavelength is recorded on the blue-sensitive rather than on the green-sensitive layer. As a result, the radiation that accounts for the characteristic green hue observed visually in nebulae is often lacking in their color reproductions. For work on emission objects, careful tests in a spectrograph should be made on samples of film in an effort to find one that will record the N_1N_2 lines on the green-sensitive emulsion. Failing this, there is only one alternative—to resort to three-color negative separation techniques that allow a choice of spectral sensitivity distribution. But do not embark lightly on such a program; it has its own multitude of problems!

Another typical problem involving spectral sensitivity at different wavelengths arises in nebulosity that emits λ 3727. This radiation often originates in the same regions of a nebula as Hα, but the film is more sensitive at 3727 Å than at 6563 Å, with the result that the ultraviolet radiation can obliterate all evidence of the hydrogen emission. This can be controlled by use of suitable filters to attenuate the ultraviolet radiation.

Figure 4 shows the typical transmittance curves for dyes used in reversal positive color film. No three dyes of this type can reproduce with *quantitative* accuracy the many hues of the visible spectrum. That is, they can theoretically reproduce all the hues of the spectrum, but not with equal saturation. Theoretically,

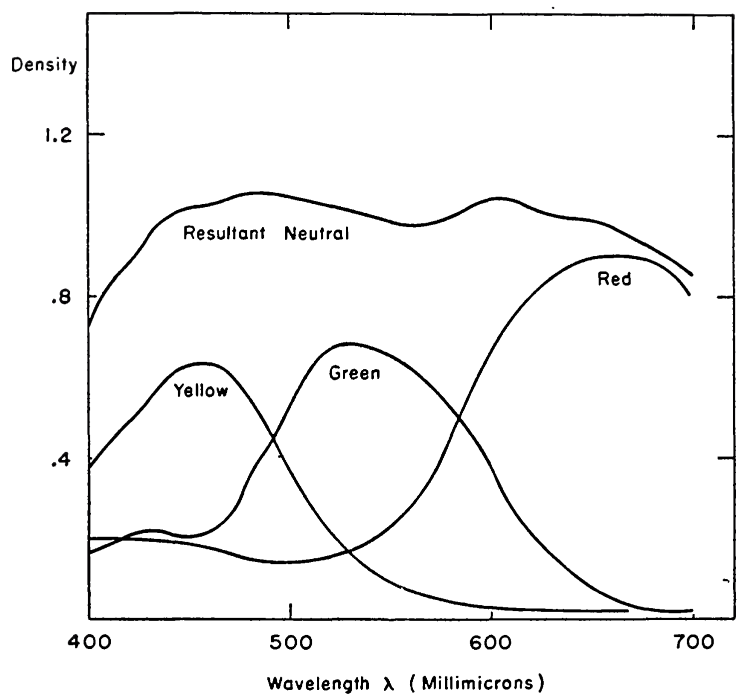

FIG. 4.—Spectral transmittance of characteristic dyes in monopack reversible color film.

special color films can be made which would reproduce emission lines with greater accuracy, but since such a film would not be useful for the usual type of color photography, it is not commercially feasible.

It goes without saying that the best possible dyes compatible with the stringent requirements of normal color photography are employed, but the dominant wavelength of the dye image may not match the wavelength of the spectral line that gave rise to the image. Reds are reproduced as a shade of red, green as a shade of green, and so on. Many intermediate hues are rendered with fair accuracy, others less so. Unfortunately, the many shades of blue and violet present in the spectrum are compressed into a very narrow range of hues in the color film; all radiation shorter than 4500 Å is reproduced as nearly the same shade of deep blue. It is highly informative to test all brands of film in this respect by exposing samples in a spectrograph. Care must be employed to use a light source with adequate energy in the ultraviolet; incandescent lamps must be avoided. Daylight can be used if all tests are made in close succession, or if allowances are made for the change in UV content under varying conditions of weather and time of day.

As already pointed out, color films are less severely taxed when it comes to recording color temperatures; the colors of stars are clearly evident, and with the application of proper controls, color films permit quick and easy detection of such objects as red and blue supergiants, or the distribution of Population I and II stars in our own and other galaxies. Actual color photometry of such stars is a subject for future investigation.

The apparent colors of stars can be greatly accentuated by utilizing extra-focal images. When a great range of magnitudes is to be covered, the film can be taken in focus, but for the last few seconds of exposure the drive-clock can be stopped to cause the brightest star images, which will be burned out on the film, to drift for a millimeter or two. These trails will not be so overexposed that color will be lost. However, it must be remembered that these trails are short exposures and therefore require a different color correction from the long-exposure images. This correction can be made either by removing the correction filters from the system during the trailing, or by using compensating filters during visual inspection of the trails. This latter device introduces errors already discussed in connection with "raw" film exposures.

The same problem is encountered with meteor trails, which are extremely short-exposure features recorded through filters intended for long-exposure correction. In the case of star or meteor trails on a film such as that shown in Figure 1, the trails will appear relatively too red if correction filters were used over the film.

Some brands of film, owing to higher inherent color contrast, accentuate relative color differences more than others. High Speed Ektachrome is particularly valuable in this respect, since its color saturation and contrast are greater than those of any other fast film.

If all film processing is done in a commercial laboratory—and this is highly recommended in view of the special equipment and experience required—only four items of equipment are needed by an observatory contemplating a color program. These are: (1) a suitable color-corrected viewing box against which the processed color films can be examined and assessed, (2) a set of color-correction filters, (3) a spot sensitometer for exposing the control strips, and (4) a color densitometer.

Many telescopes are not equipped to accommodate film, but no color emulsions are available yet on glass. Flat-field instruments require that the film be held flat behind a piece of good-quality clear glass or a glass filter. Gelatin correction filters can be sandwiched between the film and the glass plate. If filters are suspended in front of the film, they must be kept as close to the emulsion as practicable, since large-size gelatin color-correction filters are not of optical quality. In this position troublesome ghosts are encountered when two or more filters are placed in the light beam.

For use in Schmidt-type telescopes, one can anchor cut film in the middle of a photographic plate with good pressure-sensitive tape (such as Scotch Masking Tape No. 235), covering only the outer 1/8-inch on all four sides of the film. When rubbed down securely, the tape holds the film immovable for long periods. Exposures of nearly five hours have been made on films held in this manner on plates bent to a convex radius of 120 inches, with no evidence of creeping.

Sky brightness places a far more stringent limit on color exposures than on black-and-white work. Experience to date indicates that films destined for pictorial reproduction must be free of visible traces of sky fog, whereas pictures for purely visual study can tolerate twice the exposure. Films best suited for reproduction will actually appear somewhat underexposed to the uninitiated eye.

Table III gives sample exposure times for a number of objects, four of which are reproduced in Plates I and II. It should be used only as a rough guide, however. The exposure time given faint objects is usually limited by the prevailing brightness of the night sky rather than by the brightness of the object.

The Crab Nebula, Plate I, illustrates the results obtained by exposing the film without filters and making all corrections on the duplicate copy. Filters CC 40Y + CC 10C were used. The high-

TABLE III

TYPICAL EXPOSURE TIMES FOR NEBULAE AND GALAXIES ON TWO TYPES OF POSITIVE COLOR FILM AND AT THREE *f*-RATIOS

Where exposure times on an object are given for more than one instrument, the times do not necessarily indicate the relative efficiencies of the two instruments. Later exposures were often adjusted for best results on the basis of previous trials. Exposures often had to be adjusted for differences in brightness of the night sky.

			Telescope		
Object		Film	48-inch *f*/2.5	100-inch *f*/5.0	200-inch *f*/3.7
NGC 224	M 31	SA	120^m		
NGC 253		SA	120		
NGC 598	M 33	SA	90		
		HE	180		
NGC 1952*	M 1	SA			240^m
NGC 1976	M 43	SA	15		45
NGC 2024		SA	120		
NGC 2237		SA	180		
NGC 3623, 7, 8		SA	90		
NGC 4565		SA	90		
NGC 4594	M 104	SA	120		
NGC 4736	M 94	SA	90		
NGC 5194	M 51	SA	90		
NGC 5272	M 3	SA		30^m	
		HE		60	
NGC 5457	M 101	SA	90		
NGC 5904	M 5	SA		30	
NGC 6254	M 10	SA		90	
NGC 6514	M 20	SA	90		120
		HE	120		
NGC 6523	M 8	SA			90
		HE	90		
NGC 6611	M 16	SA			240
NGC 6618	M 17	SA	45		
		HE	60		
NGC 6720*	M 57	SA		120	90
NGC 6853*	M 27	SA			90
NGC 6990		SA	120		
NGC 7000		SA	180		
Pleiades and nebulosity*		SA	90		
Coma cluster of galaxies		SA	120		

SA = Super Anscochrome; HE = High Speed Ektachrome.
* Illustrated.

lights are overcorrected by this system, and the brightest portions of the image are yellowish, since very strong yellow filtration was required. It is probable that, when this object is photographed by the more accurate method of exposing through correction filters, the amorphous nucleus will appear neutral in color. The colors of the filaments and other faint portions are reasonably accurate, since the correction was determined for high densities.

The Pleiades, Plate I, were taken through filters CC 15M + CC 55C. Part of the large cyan correction was required to overcome color in the night sky due to diffuse aurora. The Dumb-Bell Nebula, Plate II, was exposed through filters CC 5Y + CC 20C. The Ring Nebula in Plate II was taken with the 200-inch Hale Telescope and later corrected with filters CC 40Y + CC 10C.

The nebulosity in the Pleiades is illuminated by scattered light from the stars, which are not hot enough to excite gaseous emissions. In the other nebulae illustrated here, the reddish light is due mainly to hydrogen and nitrogen, the greenish light to oxygen, and the blue to hydrogen and oxygen. Although helium is also present in these nebulae, its radiations contribute little to the colors. (All the photographs illustrating this article are copyrighted by the California Institute of Technology.)

This paper presents only the barest essentials involved in astronomical color photography, and is intended only as an introduction to the subject. A more detailed mimeographed report giving full particulars may be obtained upon request by those desiring to embark upon a color program.* It contains specific examples and suggested solutions of the problems that will be encountered, and the equipment is described in detail. Some of the pitfalls that can entrap the beginner are pointed out.

Color photography as it applies to astronomy is in its infancy. There are several possible lines of attack, only one of which we have begun to explore. Even the mimeographed report does not

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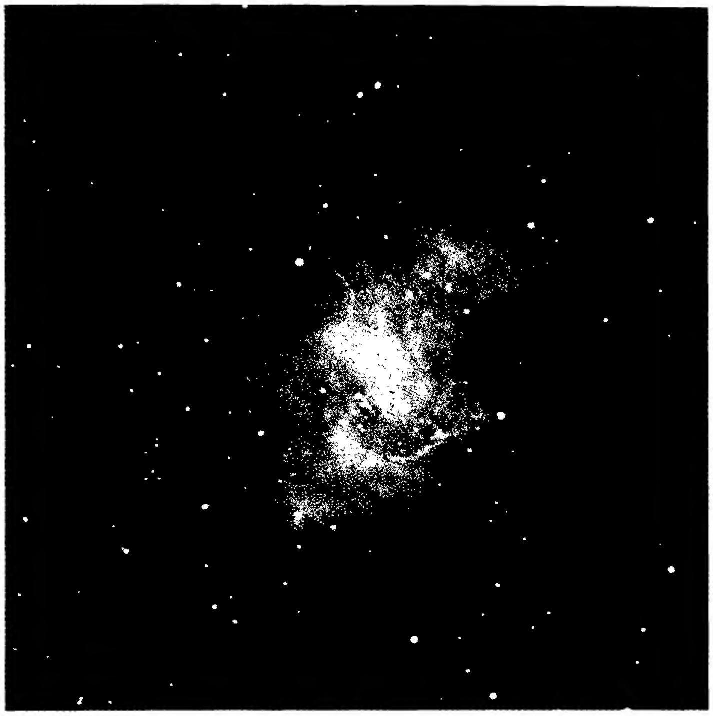
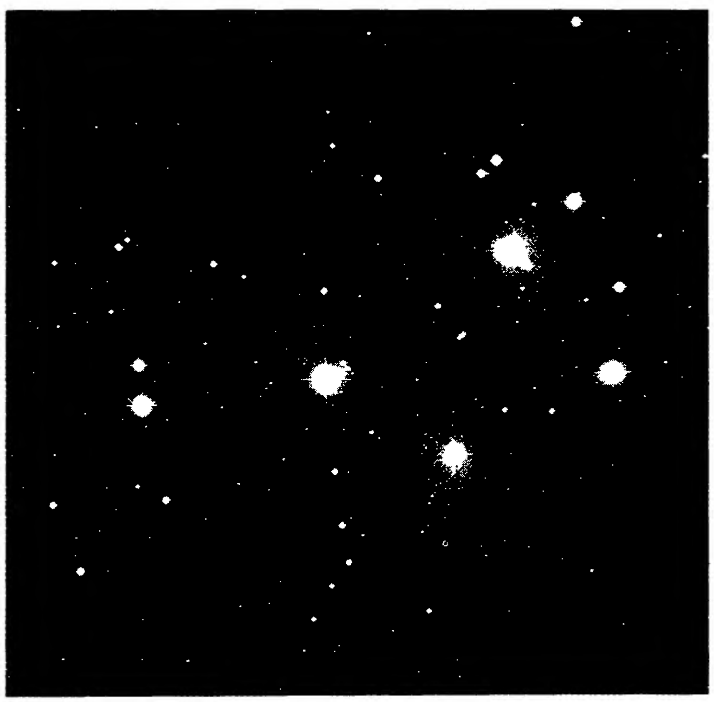
PLATE I



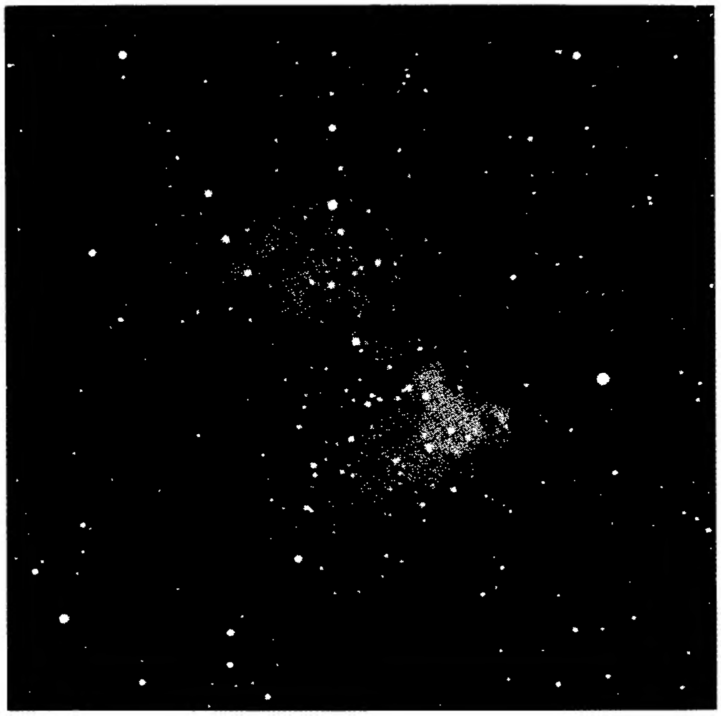
Crab Nebula, NGC 1952, M 1



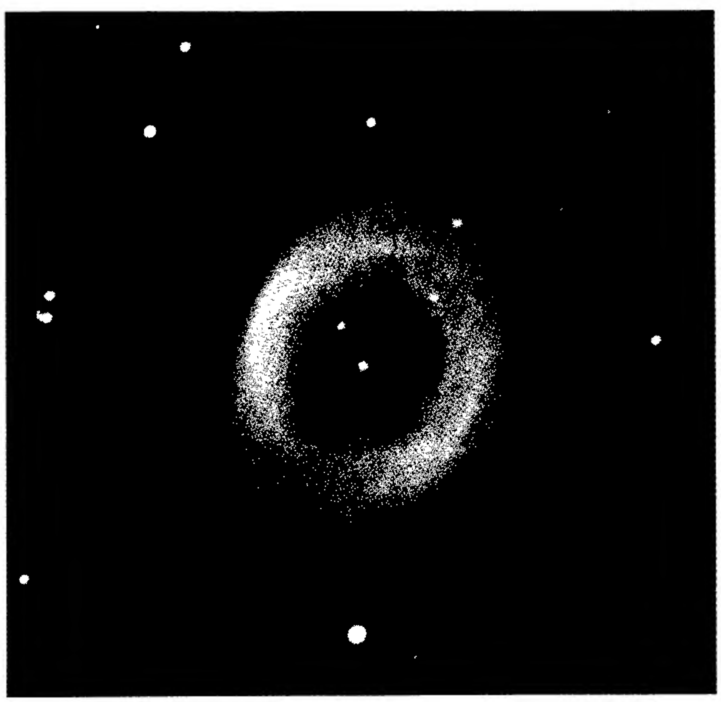
Pleiades

For details concerning Plates I and II see text and Table III.

PLATE II



Dumb-bell Nebula, NGC 6853, M 27



Ring Nebula, NGC 6720, M 57

Photographs made on Ansco Color Film.

represent an exhaustive study of the subject. There is much to be done to improve the qualitative, and ultimately the quantitative, accuracy of the system. At a comparable stage in its development, black-and-white photography was no more accurate—probably less so—for much learned from those early efforts has been applied to the color system.

It is hoped that the comments here, and specific details contained in the long report, will speed others on the path to successful color programs. The degree to which color photography furthers astrophysical research depends largely upon the ingenuity and imagination of those who apply it to their problems.

It is a pleasure to acknowledge the generous assistance of the Ansco Corporation and Dr. H. F. Nitka and George Beomler of its staff, and of the Eastman Kodak Company and their Dr. Howard Colton. During the several years that our color program was under development, they have all provided invaluable technical assistance and helpful suggestions in the preparation of this report.

[1] A. A. Hoag, *Pub. A.S.P.*, **73**, 301, 1961.

[2] R. M. Evans, W. E. Hanson, Jr., and W. L. Brewer, *Principles of Color Photography* (New York: John Wiley and Son, Inc., 1953).