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What Color is it?

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RUNNING HEAD: WHAT COLOR IS IT?

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Abstract

Color vision provides low-resolution spectrophotometric information about candidate materials for planetary surfaces that is comparable in precision to wideband photoelectric photometry, and considerably superior to Voyager TV data. This paper briefly explains the basic concepts, terminology, and notation of color science. It also shows how to convert a reflectance spectrum into a color specification. An Appendix lists a simple computer subroutine to convert spectral reflectance into CIE coordinates, and the text explains how to convert these to a surface color in a standard color atlas. Target and printed Solar System colors from a recent article (Young, 1985) are compared to show how accurate the printed colors were.

## INTRODUCTION

Color vision powerfully molds our ideas about planetary surface materials. Although the color of a substance provides only partial information about its spectrum, its spectrum cannot match a planet's if their colors differ. Hence, to be able to think of appropriate candidate materials, you must first see the correct planetary colors. If the stuff you have in mind doesn't have the right color, you don't have the right stuff.

This problem has been vividly illustrated recently by the false colors on published Voyager pictures that misled people into looking for red and orange candidate materials for the surface of Io, which is actually greenish yellow. Io was described as red or orange not only by the popular press, but by prominent scientists and respected science writers. For example, Henbest and Marten (1983) call Io "orange", and refer to a false-color picture as "true color". The book produced "in association with the Royal Astronomical Society" by Hunt and Moore (1981) says of Io, "The color was red and orange." (As one of these authors was a member of the Voyager TV team, this statement refutes the claim that team members, at least, did not believe those colors.) Morrison et al. (1982) refer to "Io's ... orange surface" in their famous book, "Powers of Ten."

In this paper, I hope to provide planetary scientists with enough guidance to the literature of color science to prevent such mistakes in the future. The amount of effort required to find colors from spectra is really quite small; I was able to determine the first correct color on Io in less than a week after deciding to do so, and most of this time was spent searching an unfamiliar literature for the information I needed. If a reflectance spectrum is already available in tabular form, the corresponding surface color can be found in about an hour with a pocket calculator.

## VADE MECUM

Although color science has existed in roughly its present form for over a century, most scientists know much less about color than they think they do. For example, a recent book (Malin and Murdin, 1984) on the "Colours of the Stars" not only presents false-colored pictures as true ones, but even gives a completely muddled "explanation" of color itself. Such widespread ignorance may explain why no correctly colored picture has ever been published from spacecraft television data, although some recent approximations (Young, 1985) are fairly close.

Part of the difficulty is due to a common experience in the educations of physical scientists: looking into a spectrometer, and seeing that monochromatic lights of different wavelengths have different colors. Many people incorrectly suppose that there is a one-to-one relation between wavelength and color, or that such a relation exists between spectral energy distribution and color. But even the existence of a unique color (under fixed viewing conditions) for each monochromatic wavelength or each spectral distribution does not imply that a converse relation exists. In fact, it cannot, because color spaces have lower dimensionality than the vector spaces needed to represent spectra; infinitely many spectra necessarily map into the same color.

For example, the fact that only the longest visible wavelengths in the spectrum appear reddish may lead to a false assumption that "red" implies "only long wavelengths"; actually, all spectral reds are slightly orange, and the "unique" or "invariable" red that looks neither bluish nor yellowish is a non-spectral color, complementary to the cyan elicited by wavelengths near 494 nm (Kelly, 1943; Le Grand, 1957, pp.211-212; Committee on Colorimetry, 1963, p.106; Wyszecki and Stiles, 1982, pp.424, 456). "Pure red" contains some short-wavelength light.

Another difficulty is the physical scientist's habit of externalizing reality. Thus, many of us wrongly assume that color is a property of electromagnetic radiation, rather than of the human visual system. But color really lies within the observer, and not "out there" in the light. Even Newton (1730; pp.123-125) realized that "if at any time I speak of Light and Rays as coloured or endued with Colours, I would be understood to speak not philosophically and properly, but grossly, and according to such Conceptions as vulgar People ... would be apt to frame. For the Rays to speak properly are not coloured. In them there is nothing else than a certain Power and Disposition to stir up a Sensation of this or that Colour."

The study of this sensation of color now belongs to the broader science of vision, an interdisciplinary area involving psychophysics, physiology, biochemistry, neuroanatomy, and other fields of medical and biological science, in addition to our more familiar areas of physical optics, radiometry, photochemistry, and optical instrumentation. These disparate disciplines are so intimately mixed in color science that one cannot easily predict where to find a particular book; for example, Le Grand's (1957) text is filed in our library with books on physiology and biochemistry, although the author's preface states that "the point of view is essentially that of the physicist"! Similarly, although Boynton (1979) states that his book emphasizes physiology, it is classified under BF (Psychology) by the Library of Congress.

The psychological aspect of color science does not mean that it is all "subjective" (in the sense of "personal" or "unreliable"), for as Boynton (1979; p.333) points out, "data of astonishing reliability" can be generated under controlled conditions. [Indeed, Appendix A shows that the precision of visual colorimetry is at least as good as that of the (B-V) photoelectric color index, for planetary colors.] It does, however, mean that one must distinguish clearly between the light stimulus and the color response it elicits.

Under fixed conditions, a particular spectral distribution does elicit a unique color sensation. Thus it is possible to determine the apparent color of a surface from its spectral reflectance. As the spectral reflectances of planetary surfaces are fairly well determined, their colors can be determined also. A standard procedure for doing this was developed in the 1940's, and will be briefly described here.

This standard procedure was followed and very briefly described by Huck et al. (1977), who correctly determined colors on Mars. Unfortunately, they then failed to reproduce the correct colors in the accompanying color plates. Furthermore, the completely false and misleading colors on all pictures published by the Voyager TV team (Smith et al., 1979a,b) -- including a picture labelled "nearly natural color" (Smith et al., 1979b, p.938) -- indicates that the cursory explanation given by Huck et al. (1977) was inadequate to educate the planetary community.

Hence, to make the explanation comprehensible, I have prefaced it by a short tutorial on color science. Kuehni's (1983) book is a more detailed, but quite short and readable introduction. Many basic concepts are briefly described and well illustrated in color in Kelly and Judd (1976), and in the excellent Kodak Publication E-74, "Color as Seen and Photographed" (now, unfortunately, out of print). Readers who want to learn more about color should then consult a standard text or reference such as the books by Le Grand (1957) or MacAdam (1981), or that published by the Committee on Colorimetry (1963). Those who are uncomfortable with the vector-space description used here will be happier with Boynton's (1979) introduction, though it barely mentions colorimetry. The current status of the science is fully reviewed by Wyszecki and Stiles (1982); this huge book contains nearly 1300 references.

## COLOR PERCEPTION

### Color and Appearance

To begin with, we must distinguish color from other aspects of appearance, such as gloss, texture, and luster.

Failure to do this led Malin and Murdin (1984; pp.35, 137) to call "gold" a color; the metal has a yellow color, but (unlike most ordinary surfaces) a metallic luster. The Committee on Colorimetry (1963, p.58) calls such use of the names of materials for color names "confusing", pointing out that "metallic luster is a characteristic of objects distinguishable from color," and recommends that "names suggesting such characteristics should not be used as color names."

## Modes of Color Perception

We must also recognize the difference in appearance between surface colors, volume colors (as in colored filter glasses), and colored lights. These and other "modes of appearance" are compared by the Committee on Colorimetry (1963, p.151). Here, we are mainly interested in the colors of surfaces (in particular, planetary surfaces).

## Related and Unrelated Colors

The perceived color elicited by a fixed stimulus depends not only on the state of adaptation of the eye, but also on the visual context in which the stimulus appears. The colors of lights seen in isolation against a black surround are seen in the "aperture" or "film" mode. These are "unrelated colors"; this is how we usually see planetary colors against the dark sky in a telescope eyepiece. Colors seen this way appear to have no black content. Without a white reference to show the intensity of the incident illumination, they appear as brighter or dimmer lights on a open-ended scale without white or black limits. Thus, the Moon appears "bright" and may seem "white" in the telescope, though it is as dark as the average asphalt paving surface. Similarly, Mars looks yellow-orange in the telescope, though it is really yellowish brown.

In a normal environment that contains familiar objects and other visual cues, such as specular reflections of the light source (D'Zmura and Lennie, 1986; Lee, 1986) the eye and brain adapt to and compensate for the color of the illumination. Colors seen in this mode are called "related colors". Here a definite brightness level appears "white"; brighter surfaces appear self-luminous or fluorescent. Instead of the "brightness" scale of lights, we perceive "lightness" of surfaces relative to the white standard.

## Color Constancy

Under such conditions, we experience "color constancy" for a given object, even though the spectral radiance it sends to the eye depends strongly on the quality and brightness of the illumination (see D'Zmura and Lennie, 1986; Maloney, 1986; Lee, 1986; and other papers in the same issue of J.O.S.A.) Thus, a wide range of different illuminants can elicit nearly the same (related) color perception from an object, although the stimuli it presents to the eye may be very different.

On the other hand, the same spectral distribution entering the eye can be perceived as very different colors in different contexts. For example, you might perceive the light of a candle flame scattered by this page as "white", if you were adapted to that light; as "orange", if you had just come from a room lit by fluorescent lamps; or as "brown" or "black" if you were standing in daylight, and saw the dimly-lit page through a small hole in a window shade.

Although these contextual and adaptive effects mean there is generally no fixed relation between spectral distribution and perceived color, a surface of given spectral reflectance <u>does</u> have a fixed, determinable color under <u>fixed</u> viewing conditions. Critical color comparisons require both a fixed angular size of stimulus and a fixed surround (usually a neutral gray of about the same lightness as the samples to be compared), as well as a fixed spectral illuminant.

In particular, a surface of given spectral reflectance has a fixed and reproducible (i.e., "constant") related color when viewed in typical daylight conditions. The method for determining that color from the surface's spectral reflectance is described below. But first, we must consider color nomenclature.

## Color Spaces

All visible colors can be arranged in a continuous three-dimensional sequence or "color space". This empirical fact has been known for centuries. However, the choice of coordinate axes is quite arbitrary, and a wide variety of systems has been used (cf. Wyszecki and Stiles, 1982, pp.164-169, 486-513, and 824-884). Some of these are illustrated by Kelly and Judd (1976).

Human color space is three-dimensional because our eyes contain three types of cone-shaped receptors, each with its own type of spectral response, that contribute to color vision. We may crudely describe the sensations they produce as "blue", "green", and "red". However, the detected signals are immediately processed in the eye and brain to yield a brightness channel (roughly, the sum of the green and red cone signals); a red-green channel (their ratio); and a blue-yellow (blue vs. red + green) channel. These "opponent mechanisms" modify the signals before we perceive them, so perhaps the most natural dimensions of color space are black/white, red/green, and yellow/blue. Such natural basis vectors appear in both psychophysical (Krauskopf et al., 1982) and physiological (Derrington et al., 1984) experiments.

## Brown

The black/white mechanism helps explain why unrelated planetary colors seen in the telescope show no black content: adaptation to the black surround drives this channel toward white. On the other hand, when we see typical planetary materials as related surface colors in the laboratory, those with reduced lightness can "cause new sensations to appear, especially in the region of orange, yellow, and greenish yellow. If the lightness of the specimens is low these colours appear as chestnut, brown and olive-green respectively" (Le Grand, 1957, p.220).

Similarly, Kelly and Judd (1976) say that "...the term yellow is commonly used to designate not only a certain hue range but also a high lightness range within this hue range. Dark colors of the same hue as yellow are commonly termed olive or olive brown. Common usage limits the term orange even more strictly; it is taken to refer not simply to a range of yellow-red hues but also to a medium-lightness range and a high saturation range. Colors of the same hue but of lower lightness and saturation than the orange range are called browns."

Because so many planetary surfaces are brown, it is necessary to emphasize that this color is perceived when any dark yellowish surface is seen as a related surface color. It is not, as Malin and Murdin (1984; p.137) say, a "non-spectral" color; that term is reserved for the purple hues that cannot be matched by any mixture of monochromatic and white light. (They compound the confusion by saying that "non-spectral ... means that it cannot be made simply by combining red, green, and blue lights in an additive process." The non-spectral purples are in fact made by adding red and blue lights; moreover, as will be shown below, there are even spectral colors that cannot be matched by adding red, green, and blue lights! They have confused the distinction between surface and aperture modes with the difference between spectral and non-spectral colors.)

## Munsell Renotation for Surface Colors

The system of arranging surface colors that is best known in the United States is that introduced by A.H.Munsell about 1905; with minor modifications, the same system is available today from Munsell Color (Macbeth Division of the Kollmorgen Corp., 2441 N.Calvert St., Baltimore, MD 21218). The standard colors in this system are available as both glossy and matte-finish painted papers; various sets of these colors are published in different editions of the Munsell Book of Color.

The Munsell system arranges all colors cylindrically about a vertical axis whose direction represents the sensation of lightness. A pure white magnesium oxide block is assigned Munsell value 10/; value 5/ represents a medium gray; and value 0/ is perfectly black. The physical quantity that is related to Munsell value is visual reflectance. However, the nonlinearity of the human visual system makes the Munsell value scale lie between the square and cube roots of reflectance, so that value 5/ corresponds to about 20% reflectance. The precision of visual judgments is one or two tenths of a Munsell value step (Nickerson, 1947, p.167; Kelly and Judd, 1976, p.A-13). This corresponds to about 4% precision in visual reflectance, for typical surfaces.

All shades of gray form the central vertical axis of the cylindrical Munsell coordinate system. The azimuthal coordinate is hue (red, yellow, green, blue, purple, etc.), which is what is often meant by the word "color" in casual conversation. The five main hues just named are equally spaced; between them lie secondary combinations such as YR for "yellow-red" and GY for "green-yellow". Each of the 10 named hues is subdivided into 10 numerical subclasses, rather like stellar spectral types (which are also based on visual estimates). Thus, a pure red has hue 5R; orange is 5YR; and the borderline between them is 10R or 0YR. The precision of hue matches for experienced observers is about 1/4 Munsell hue unit for highly saturated colors (Kelly and Judd, 1976); a more typical value is 0.6 in hue (Nickerson, 1947).

The amount by which a color differs from gray (i.e., the radial coordinate in the Munsell system) is called "chroma". A more familiar word for a closely related concept is "saturation". The pure spectral colors have maximum chroma, which is about 20 (because the most saturated red pigment available to Munsell had about half this saturation and was given chroma 10; see p.74 of Birren, 1969). White, grays, and black have chroma zero, and are thus sometimes called "achromatic colors", to distinguish them from the "chromatic colors". The precision of visual color matching between observers is about 0.3 Munsell chroma unit.

The complete Munsell specification for a surface color is given as Hue Value/Chroma. For example, 5Y 8.5/12 is a medium yellow hue (5Y) of high lightness (value 8.5) and saturation (chroma 12), about the color of dandelion blooms. The conventional representation of the Munsell system is left-handed; i.e., if the value axis increases upward, the hue subdivisions increase numerically clockwise, looking down along this axis. Hue-chroma planes (i.e., surfaces of constant value) are drawn with the 5R ray toward the top of the page, with yellow, green, blue, and purple following in clockwise order.

Munsell notations are widely used in industry, not only because they are easily determined by quick visual comparisons with Munsell color standards, but also because they provide quantitative information of high precision. Appendix A shows that the precision of visual color matching is comparable to or better than that of wideband photoelectric systems such as UBV, and much better than spacecraft television systems have done. The utility of visual color measurement has been recognized in some fields, such as geology, but is largely neglected by planetary scientists.

Munsell renotations are nearly uniformly spaced perceptually. The original notations were established visually, without any reference to spectrophotometry. However, spectrophotometric data were used 40 years ago to make the system smoother in a stimulus color space, described below. This minor revision caused the "renotations" to differ very slightly from the original notations in older editions.

The December, 1940, issue of J.O.S.A. was devoted to a detailed investigation of the old Munsell system, including the history of its development. The Munsell renotations were adopted by the American Standards

Association in 1951 (ASA-Z58.7.1,2,3). The system is described and well illustrated in "Webster's Third New International Dictionary of the English Language Unabridged", under the entry "color". Birren (1969) gives a thorough description of Munsell's system.

## STIMULI AND COLORIMETRY

### Illumination and Surface Colors

The spectral energy distribution of the light stimulus reflected from a surface to the eye depends both on the spectral reflectance of the surface and on the spectral energy distribution of the light that illuminates the surface. The Commission Internationale de l'Eclairage (CIE) established three standard illuminants for colorimetry in 1931. Illuminant A represents light from the full radiator (black body) at 2856 K, and is closely approximated by a tungsten-filament lamp with this correlated color temperature; Illuminant B was intended to represent direct sunlight, excluding the light of the blue sky; and Illuminant C was intended to represent average daylight (a mixture of transmitted sunlight and diffuse skylight).

Subsequently, Illuminant C was found to be slightly deficient for some purposes, mainly connected with fluorescent materials. Planetary surfaces are not appreciably fluorescent, so this problem is minor; and in any case we will need to use a great deal of work done with Illuminant C. However, it will eventually be replaced by the better daylight approximation designated as D65.

## Stimulus space and metamerism

Just as we have used the Munsell notation to describe perceived surface colors, we may define a three-dimensional color space for the spectral radiance functions of the colored stimuli. (For any definite illuminant, such as CIE Illuminant C, this is equivalent to using the spectral reflectance functions for surface colors.) However, even if we restrict attention to bounded, continuous functions, this set is infinite in dimension (Hilbert space; see Parkkinen and Jaaskelainen, 1987). Distinguishable color stimuli are only the projection of this infinite-dimensional space of spectra onto a three-dimensional subspace of colors. In this respect, color vision is like 3-color broadband astronomical photometry (Young, 1974a).

The projection vector (whose components are continuous functions of wavelength, and which is orthogonal to the three-dimensional subspace of color vision) can be determined only by measurements made by human observers, to determine sets of physically different color stimuli that are visually identical. Such stimuli are called metameric, or are said to be metamers of one another. Any stimulus that is not monochromatic has an infinite number of metamers.

The spectra of metamers differ by functions whose projection into human color space is null. Table I(3.8.2) of Wyszecki and Stiles (1982) gives 27 such "metameric blacks", and their Fig. 7(3.8.2) shows 12 wildly different spectral reflectance functions of surfaces that would appear the same shade of gray under illuminant C.

Fortunately, statistical studies of many natural and artificial surfaces (e.g., Maloney, 1986; Parkkinen and Jaaskelainen, 1987) show that well over 90% of the variance among real reflection spectra is accounted for by the first 3 principal components. Thus, even though about seven parameters are needed to produce an essentially perfect fit to such data, so that about seven dimensions are in fact required to represent actual surface spectral reflectance functions accurately, it turns out that the three dimensional subspace of color vision captures the bulk of significant information about real colored surfaces.

As Maloney (1986) points out, the spectral reflectances of real surfaces are band-limited functions, due mainly to the width of electronic absorptions in solids. That is why only about seven dimensions are needed to represent the spectral reflectances of real surfaces. This band-limited character has allowed the broadband filters used in spacecraft TV systems to capture most of the significant information about planetary surface spectra. It also explains the utility of broadband photometry in characterizing asteroid surfaces. Thus, the undersampling of object spectra by all these systems, including the eye, does not produce severe aliasing problems; metamerism is not a serious nuisance in practice.

Color matching and primaries

The metamers can be found by means of color-matching experiments. In a typical experiment, three highly saturated lights of widely different hues are chosen as "primaries". The choice of primaries is quite arbitrary; often monochromatic or nearly monochromatic lights are used. It turns out that any color can be matched by some linear combination of these primaries.

However, it is not true, as Malin and Murdin (1984; pp.35, 60-61) assert, that "All the colours of the spectrum ... can be mimicked by combinations of different intensities of ... blue, green, and red," nor that "coloured lights can be mixed to give pure spectral hues". The "linear combinations" in these cases involve negative coefficients; spectrum colors other than those in the set of primaries would require negative amounts of some complementary primary, to be matched by direct addition. As negative intensities do not exist, this is impossible.

However, the negative coefficients can be evaluated by modifying the matching experiment. If the appropriately scaled amounts of the primaries are denoted by A, B, and C, and some test stimulus D is equivalent to A + B - C, we note that D = A + B - C can be rearranged to read C + D = A + B. Hence, the additive mixture of lights A + B should match the additive combination C + D. Thus, if we add the primary requiring a negative coefficient to the test stimulus, we can extend the experiment to include colors outside the region of direct additive combinations. (If the primaries are not monochromatic, two of them may need such treatment to match certain monochromatic stimuli.)

Tristimulus values

The amounts of the three primaries required to match a given color are called its "tristimulus values". Negative tristimulus values occur in all color-matching experiments with physically realizable primaries (MacAdam, 1981, p.11; see Fig. 1). The reason for this is well explained by Boynton (1979, pp.128-144); briefly, it is due to the overlap of the cones' spectral responses, which makes most monochromatic stimuli excite more than one kind of receptor. There is no light, for example, that stimulates only the "green" cones and no others.

Any color stimulus can be represented by a point in a three-dimensional "tristimulus space" whose coordinates are its three tristimulus values. If actual lights are used as primaries, all color stimuli project into points that are contained in a half-space (i.e., they lie on one side of a plane through the origin, which is the zero stimulus.)

Because the cones' spectral response functions overlap, the subspace of real colors does not fill this half-space, but define a cone whose vertex is the origin and whose base is a convex curve. Spectrally pure lights lie along the elements of this cone. The colors that can be produced by additively combining any three primary lights fill a triangular pyramid lying entirely within the cone; each primary lies along one edge of the pyramid [see Fig. 1(3.2.2), p.121 of Wyszecki and Stiles (1982)]. No matter what three lights are used as primaries, there are always colors lying between the pyramid and the (convex) cone that cannot be produced with positive tristimulus values. These are the colors that require negative values of one (or two, if the primaries are not spectrally pure) of the primaries.

Color-matching functions

If we plot the tristimulus values required to match monochromatic lights of constant power as functions of wavelength, we call the resulting functions the "color-matching functions" with respect to the chosen primaries. Thus, Fig. 1 shows the color-matching functions with respect to primaries at 700 nm, 546.1 nm, and 435.8 nm. Color-matching functions are conventionally denoted by lower-case letters, with an overbar as a reminder that they refer to the same power at each wavelength. Thus, the CIE color-matching functions with respect to the primaries R, G, and B shown in Fig. 1 are denoted by $\bar{r}$, $\bar{g}$, and $\bar{b}$.

The choice of primaries is quite arbitrary, so long as their vectors in color space are not coplanar. Each set of primaries is a different set of basis vectors for the same three-dimensional color space. Any three linearly independent combinations of these color-matching functions span the same three-dimensional subspace of all possible spectral functions, and hence are also color-matching functions (with respect to a new set of primaries).

In particular, we can choose combinations of color-matching functions that are entirely positive. These are much more convenient to work with (for example, they can serve as spectral response functions in a colorimeter), but they refer to primaries that lie outside the range of physically realizable colors. In 1931, the CIE adopted such a set of positive color-matching functions, denoted by $\bar{x}$, $\bar{y}$, and $\bar{z}$ (see Fig. 2), which have been so useful and accurate a representation of normal human color vision that they remain in standard use today.

The CIE primary X represents a red stimulus more saturated than any real stimulus, and of hue complementary to 496 nm; Y is a green primary the same hue as monochromatic light at 520 nm, but more saturated; and Z is a blue primary more saturated than 477-nm light (MacAdam, 1981, p.11). The color-matching function $\bar{y}$ was chosen to be the so-called "visibility" or "luminosity" function of the eye, which shows the relative ability of each wavelength to produce the sensation of brightness. The CIE color-matching functions are tabulated in all reference works on colorimetry (e.g., Le Grand, 1957, p.454; MacAdam, 1981, pp.13, 59; Wyszecki and Stiles, 1982, pp.725-753).

Because the color-matching functions show the relative amounts of the primaries required to match monochromatic light at each wavelength, the tristimulus values (X, Y, Z) of any spectral distribution r( ) are just the wavelength integrals of the products of r( ) with each of the color-matching functions $\bar{x}$, $\bar{y}$, and $\bar{z}$, respectively. In practice, these integrals are well approximated by sums (see Chapter 5 of MacAdam, 1981). Appendix B gives a simple

FORTRAN 77 subroutine for computing CIE tristimulus values of surfaces under Illuminant C from spectral reflectances.

Notice that these color-matching functions need not resemble the fundamental response functions of the receptors in the eye, but are just some linear combinations of them. Indeed, color-matching data from normal individuals do not suffice to determine the eye's primary response functions. However, data from color-deficient individuals can be used to deduce the action spectra of the missing visual pigments, and these functions agree reasonably well with absorption spectra measured microspectrophotometrically on individual cones (see Fig. 3).

Chromaticity Coordinates and Dominant Wavelengths

Lights of the same spectral distribution but different brightness have tristimulus values that differ only by a constant factor. It is conventional, for convenience in two-dimensional plotting, to normalize the X and Y coordinates by the sum (X + Y + Z); the normalized coordinates

$$x = X/(X + Y + Z) \quad \text{and} \quad y = Y/(X + Y + Z)$$

are called "chromaticity coordinates". Two lights of the same color except for brightness have the same chromaticity coordinates. In dealing with colored lights, it is often acceptable to ignore that third dimension of color space, so a two-dimensional chromaticity diagram shows the information of interest.

Similarly, we can compute the chromaticity coordinates of surfaces from the spectra of the light they reflect, if the spectral distribution of the illuminant is given. Two surfaces that differ only in lightness under a given illuminant have the same chromaticity coordinates. In this case, using a two-dimensional chromaticity diagram may reject important information; for example, "pieces of chocolate and orange peel have the same chromaticity coefficients and differ only in lightness" (Le Grand, 1957, p.220). Also, notice that because the spectral distribution of the illuminant is multiplied by the spectral reflectance of the surface within the integrand, two surfaces that are metamers under one illuminant are generally not metamers under other illuminants.

The chromaticity coordinates of CIE Illuminant C are ($x$ = 0.3101, $y$ = 0.3163). Any point along a line joining this "white" stimulus to a point on the spectrum locus represents a color that can be matched by a mixture of white light from Illuminant C and monochromatic light, whose wavelength is called the "dominant wavelength" of the colors along the radial line. The fraction of monochromatic light in this mixture is called the "excitation purity"; it is the fraction of the distance from C to the spectrum locus where the point falls on the line.

Thus, the CIE chromaticity space has orthogonal Cartesian coordinates (x, y, Y), and is usually drawn with the Y axis vertical. The axes form a right-handed set, so that the spectral hues follow a counterclockwise order from red to blue in an (x, y) plane. Notice that this is the reverse of the usual Munsell ordering.

## FROM CHROMATICITY TO COLORS

It is essential to realize that chromaticity coordinates alone specify nothing beyond metamerism. That is, two surfaces with the same (x, y, Y) coordinates in a given illuminant, or two lights with the same values of (X, Y, Z), appear identical to the CIE standard observer. The coordinates themselves do not tell us <u>what</u> colors the eye sees; nor are equally spaced colors in chromaticity space at all equally spaced perceptually.

However, the mapping of points from a stimulus space (e.g., CIE chromaticity coordinates) to a perceived color space (e.g., Munsell renotation) for given viewing conditions can be determined empirically. Fortunately, this transformation has been determined for related surface colors by using Munsell samples viewed in daylight (Newhall et al., 1943). The extensive tables they published have been reprinted by Wyszecki and Stiles (1982; pp.840-861) with graphs of the corresponding loci of constant Munsell hue and chroma for each integer of Munsell value. Thus it is very easy to transform a color specification from one system to the other, using either numerical or graphical interpolation, in either direction.

Thus, the standard procedure for converting a spectral reflectance into a perceived related surface color has two steps. First, convert the spectral reflectance into CIE chromaticity coordinates, using illuminant C. (The program listed in Appendix B does this if the reflectance is sufficiently smooth to allow adequate sampling at 100-A intervals.) Second, use the tables or graphs mentioned above to convert the chromaticity coordinates to a Munsell renotation. One can then go to the Munsell Book of Color and see what the color looks like, using daylight illumination.

COLORS AND SPECTRA

Before applying these methods to particular objects, we may find some simple classes of spectra instructive. The first, a simple linear ramp, is similar to the spectra of "many natural materials" including "many ... minerals" (MacAdam, 1981; p.128), and particularly Mercury, Moon, and some asteroids. MacAdam shows that the colors of <u>all</u> objects with such spectra have the same dominant wavelength (580.1 nm) and differ only in purity.

Although Munsell hue is not uniquely related to dominant wavelength, owing to the Abney and the Bezold-Brücke effects, all colors with this dominant wavelength (in stimulus space) have Munsell hues (in perceived color space) near 1Y. Their Munsell value can be computed rather precisely from the V-band ("visual") albedoes, thanks to the historic link between human vision and the modern V magnitude scale. As the maximum chroma of a ramp that starts at zero reflectance at 400 nm is /8, and any linear spectrum can be regarded as the sum of such a ramp and a flat (white) pedestal, the Munsell notation for an object with such a linear spectrum can almost be written down on inspection of the spectrum.

Planets such as Mars and Io have spectra that are better approximated by step functions, again allowing for a pedestal that can be estimated from their reflectance at short wavelengths. The colors corresponding to such spectra are a little more difficult to understand.

As the wavelength at which the step occurs moves into the visible spectrum from short wavelengths, the initial effect is to reduce the integral Z very quickly, and to decrease X by a much smaller amount (owing to the small short-wavelength lobe of the $\bar{x}$ color-matching function). The dominant wavelength produced is, of course, the complement of the short-wavelength corner of the chromaticity diagram. MacAdam (1981; p. 5Ø) gives the complement with respect to Illuminant C for these short wavelengths as 567 nm. Because some "red" response (X) is removed along with the "blue", the initial hue is a greenish white or pale yellow green, near Munsell hue 6 GY (see Fig. 4). This agrees exactly with Sill's (1973) description of the color of sulfur in liquid nitrogen as "a faint pale green".

However, the "blue" channel contributes practically nothing to the sensation of brightness, and hence nothing to the Y integral. Consequently, the apparent lightness of such a hypothetical surface is hardly decreased until the transition wavelength reaches about 5ØØ nm, where the Y integral begins to decrease (see Fig. 5). Furthermore, until it does, the green/red ratio remains nearly constant. Thus, all such surfaces, with a step in the spectrum between 4ØØ and 5ØØ nm, have very nearly the same dominant wavelength and very nearly the same hue (near 3 GY). Only the purity (in stimulus terms) or chroma (in perceptual terms) changes as the step moves to longer wavelengths.

As the step moves past 5ØØ nm, the Y integral begins to decrease. The surface becomes darker and redder. The excitation purity is nearly 1ØØ% for all these colors. The dominant wavelength passes through a region in which the eye is remarkably sensitive to small changes; for example, saturated colors of Munsell hues 2.5 Y and 10 YR differ in dominant wavelength by only about 2.7 nm, corresponding to motion of the step from 531 to 539 nm (see Fig. 4). An experienced observer can distinguish ten hues in this range.

In fact, over the whole range of "yellow" Munsell hues, from 10 YR (= 0Y) to 10Y, the dominant wavelength of saturated colors changes only 10 nm, corresponding to displacement of the spectral step from 501 to 539 nm. Thus, the very obvious change of 2.5 Munsell hue steps from one page of the Munsell book to the next corresponds, on the average, to less than 10 nm in the step wavelength, or 2.5 nm in the dominant wavelength.

This is comparable to the spread in half-peak wavelengths among the Io spectra within each individual color class on Fig. 4 of Soderblom et al. (1980): nominally similar regions on Io have, in fact, colors that are readily perceived to be very different by a color-normal observer. Human color vision makes finer distinctions among surfaces with such reflectance spectra than Soderblom et al. (1980) considered significant. Thus, a quantitative color specification, such as a Munsell renotation, actually contains more detailed information about such surfaces than the Voyager TV data can reliably supply.

Indeed, normal color perception is so sensitive to small differences in spectral reflectance among yellow surfaces that such surfaces may be more readily distinguished by their colors than by plotting their spectra. Fig. 6 shows reflectance spectra of two rather similar yellow surfaces that differ by one Munsell hue unit. The eye can distinguish hue differences of about 1/4 hue step between such saturated colors. Thus, about 3 more equally-spaced colors could be interpolated between these; but it would be difficult to draw another three distinctly different curves between those shown in Fig. 6.

This extreme sensitivity accounts for the narrowness of the part of a spectrum that appears yellow. It also accounts for the difficulty in reproducing such colors accurately on the printed page, and for the very large hue shifts produced by the Voyager TV team by reproducing pictures a few dozen nanometers to the red of the bands in which they were taken.

The remarkably different character of the perceived changes as the step passes 500 nm, from mainly a change in chroma at nearly constant hue and brightness (on the short wavelength side of 500 nm) to large changes in hue and brightness at nearly constant chroma (on the long wavelength side), is due to the strong overlap of the spectral sensitivities of the red and green cones, on the one hand, compared to their very small overlap with the response curve of the blue cones, on the other. For steps below 500 nm, only the blue/yellow channel of color vision is strongly affected by step position. For longer step wavelengths, this channel is forced to its yellow extreme, and both the red/green and black/white channels are sensitive to the wavelength at the step.

NONLINEARITY AND COLOR NAMING

Because the red and green cones have so nearly the same spectral responses, the red-green opponent mechanism cancels much of their common response and makes small nonlinear differences between the red and green channels easily visible in the yellowish hues. For example, the green content of the greenish yellows is hardly visible at high Munsell value, but adding a small amount of gray or black to them makes the green stand out prominently. A moderate yellow like Munsell 5Y 7/7 appears moderate olive if its reflectance is reduced 5 or 10 times, to 5Y 3/7. Likewise, 8Y 9/2.5 is just pale yellow, but 8Y 4/2.5 is grayish olive (Kelly and Judd, 1976). I have pointed out elsewhere (Young, 1984) these effects in the perceived colors of Jupiter, which appears pale yellow when seen as a bright light against black space, but looks olive when seen with the much brighter Moon, which lowers the perceived lightness of Jupiter.

Furthermore, a pale orange yellow like 7.5 YR 9/4 looks pale yellowish pink when desaturated to 7.5 YR 9/2. At Munsell hue 6YR, which is slightly to the yellow side of the purest orange hues, all colors lighter than Munsell value 6.5 and less saturated than chroma /6 are called yellowish pink, brownish pink, or pinkish gray or white. Thus, although the "pinks" dominate light colors on the purplish side of red (near Munsell hue 2.5 R), an orange yellow will be called "pink" if it is sufficiently light and unsaturated.

These effects help explain the pinkish color sometimes attributed to Io by observers who see it next to greenish-yellow Jupiter. Only a small change in the adaptation of the eye, from white sunlight to the greenish yellow of Jupiter, could shift Io's perceived hue from its actual pale greenish yellow near Munsell 6Y to 8YR, the edge of the yellowish pinks.

Furthermore, the red and brown colors often seen on Jupiter itself are due to the well known expansion of the range of perceived colors in a scene of limited color range. For example, Hurvich and Jameson (1960) showed a complex display of low-saturation yellowish greens, not very different from the range of stimuli presented by Jupiter and Io at the telescope, to seven observers in a laboratory setting. The perceived hues included the pure red hue Munsell 5R (see their Fig. 12). The lightest areas in the same display were near Y=Ø.6 (Munsell value 8.1), but areas only slightly darker with Y=Ø.4 (value 6.8) appeared as dark as Y=Ø.1 (value 3.7; "brown" appears below value 6.5). Thus, the human visual system considerably enhances low-contrast images.

This exaggeration of the gamut of colors perceived in a scene of very limited color range, such as Jupiter presents at the telescope, probably accounts for the acceptance of highly exaggerated false-color pictures as realistic by the Voyager imaging team. Although, as Smith is reported (Goldberg, 1979) to have said, "That is what Jupiter looks like to the eye", it is not what Jupiter would look like if we could see it in a normal terrestrial scene with a full range of colors.

## IO

The reflectance spectrum of Io is well known, both globally from ground-based spectrophotometry, and locally from Voyager TV measurements through filters. It is marked by a great deficiency of what Newton called violet and indigo rays, being rather flat at longer wavelengths. The procedure described above was applied to the Io spectra by Young (1984); the resulting colors were pale, grayish, and somewhat greenish yellows, in the NBS-ISCC naming system.

Newton (1730; p.164) found that "the mixture of all Colours but violet and indigo will compound a faint yellow, verging more to green than to orange." This describes exactly both the reflectance spectrum and the color of Io (Young, 1984, 1985). He continues, "Thus it is by the computation: And they that please to view the Colours ... will find it so in Nature."

So said Newton; and so say I. They that please to view the colors will find them closely represented in Young (1985). How closely? Figs. 7-12 compare the target colors (asterisks) with those that were actually printed (circles) in four different parts of the press run. The symbol size in these diagrams is comparable to the precision of visual color matches in each dimension. As these diagrams use Munsell (i.e., perceived color) coordinates rather than chromaticity (i.e., stimulus) coordinates, they are approximately perceptually uniform.

While most of the planetary colors published in (Young, 1985) were fairly close to the actual planetary colors, Mars was appreciably too red. Figs. 7 and 8 show that the true color of Mars is intermediate between the printed colors of the "Mars" color patch and the "Titan" patch; if anything, the latter is closer to the color of Mars. This, with the excessive saturation of the colors printed for the Moon and Mercury, was due to the difficulties of the printing process. It is not possible to print colors with very high accuracy, as one sees from the separation of the printed colors from their targets, nor with very high precision, as one sees from the scatter among the four samples.

The Io picture at the top of p.400 (Young, 1985) was about the correct hue (see Fig. 11); the picture at the bottom of the page was slightly too green (see Fig. 9). As both ground-based and Voyager pictures show, the belts of Jupiter are similar in color to the average color of Io, and hence considerably less saturated than the top Io picture, which includes one of the most saturated areas on Io. Although Jupiter's bright zones were reproduced correctly, the belts were much too red and too dark, even in the low-contrast version.

It is unfortunate that no really true color picture of Jupiter has ever been published from Voyager data.

## HOMILETIC DISCUSSION

Color is so important a part of vision that we habitually rely on it to identify materials, including those that may occur on planetary surfaces; to distinguish between good and unpleasant foods, as in rejecting "green" fruits; and even to ensure our personal safety by means of colored traffic signals and navigational lights. This sensation not only "colors our language" but also our thinking; and we can clarify both by understanding color well.

Planetary scientists are already accustomed to dealing with interdisciplinary problems. If, to understand color, we must acquaint ourselves with some unfamiliar branches of science, this is hardly a new situation. And the reward is well worth the effort, for we both receive and distribute most of our information visually.

I have heard some scientists argue that "color isn't important", and that "all the science is in the numbers". (If they really believed that, they would not show color slides at DPS meetings!) This is a naive attitude; color <u>does</u> influence our thinking, whether we recognize it or not. The enormous importance of color was recognised by the award of the 1908 Nobel prize in physics to G.J.Lippmann for his development of a method of color photography so imperfect it is now almost forgotten. To ignore the importance of color is to risk being led astray by incorrect colors. At the Workshop on Volcanic Flows on Io, there were gasps of amazement when the customary false-color Voyager pictures were replaced by more accurately colored ones, and one scientist said he would have done his work differently if he had seen the correct colors earlier.

Not only will we be less likely to deceive ourselves with falsely colored pictures, but we may prevent a public-relations fiasco in dealing with a public that can be resentful at being misled, and that supports our efforts with its taxes. Accurately colored pictures are one thing the public definitely expects of us, and are by far the most accessible product we can produce for the scientifically untrained layman. Neglecting color could be hazardous to the health of the whole planetary research program.

Let me recall a few words of Tim Mutch (1978), who wrote, "we had no intimation of the immediate and widespread public interest in the first color products." He went on to describe the steps that led to publication of pictures of Mars with a blue sky. "Several days after the first release, we distributed a second version, this time with the sky reddish. Predictably, newspaper headlines of 'Martian sky turns from blue to red' were followed by accounts of scientific fallibility. We smiled painfully when reporters asked us if the sky would turn green in a subsequent version."

I had hoped that the lessons of Viking had been learned. To quote Tim Mutch again, "we were dismally unprepared to reconstruct and analyze the first color picture. ...we failed to appreciate ... many subtle problems which, uncorrected, could produce major changes in color." This seems to remain true.

# APPENDIX A

The precision of visual color matching was investigated by MacAdam (1942) in a classic paper. His results of most interest to the planetary scientist are those for neutral and slightly yellowish colors, corresponding to those that commonly occur on planets. The chromaticity of the point closest to Illuminant C was (x, y) = (Ø.3Ø5, Ø.323), at which the long semiaxis of the ellipse that represents the standard deviation of visual color matches was Ø.ØØ23, and the short semiaxis was Ø.ØØØ9 in length. For the nearby point at (Ø.385, Ø.393), corresponding to light yellow surfaces, the semiaxes were Ø.ØØ38 and Ø.ØØ16; in both cases, the major axis lay nearly in the direction of increasing yellow saturation.

We may compare these values for the eye's sensitivity to small color differences to that of broadband photoelectric photometry in the UBV system. Many planetary and mineral surfaces have a nearly linear variation of reflectance with wavelength, as discussed in the text; so we may ask what slope change in the reflectance of a nearly neutral gray surface is detectable to either the eye or the photometer.

If we adopt 441.5 nm and 55Ø nm as the effective wavelengths of the B and V passbands, a slope in reflectance of Ø.ØØ848%/nm will make the (B - V) color index of the reflected light Ø.Ø1 mag redder than that of the Sun. This is comparable to or less than the smallest difference in (B - V) usually detectable in a single observation. For example, FitzGerald (1973) found a standard deviation of Ø.Ø11 mag in (B - V) in comparing a number of catalogs; and the errors given by Johnson and Harris (1954) for the original UBV standard stars correspond to Ø.Ø2 mag per observation in (B - V).

The slope of Ø.ØØ848%/nm required to produce a change of Ø.Ø1 in the (B - V) color index produces a surface with chromaticity coordinates x = Ø.3124, y = Ø.3182 under Illuminant C, corresponding to Munsell chroma /Ø.13, or an excitation purity of about 1%. This point lies about Ø.ØØ3Ø units in (x, y) space from Illuminant C. According to MacAdam (1942), the standard deviation of color matches in this region of color space is at worst Ø.ØØ23, in about the direction this point lies from Illuminant C.

In other words, a spectral slope change that alters (B - V) by Ø.Ø1 mag differs from a flat spectrum by Ø.ØØ3Ø/Ø.ØØ23 = 1.3 times the standard deviation of visual color matches, although it is a little less than the standard deviation of (B - V) color-index measurements. This is consistent with MacAdam's statement that the first visually detectable step from white corresponds to Ø.2 to Ø.7%

excitation purity, depending on the wavelength. The eye is thus about twice as precise in detecting small changes in spectral slope of a low-saturation surface as is UBV photoelectric photometry.

When we consider that the eye's error is only 0.0009 or less than half as large in the orthogonal direction (roughly that of hue), it becomes even clearer that the eye is more precise than UBV photometry for detecting small color differences among nearly neutral or pale yellowish surfaces, such as are typical of planets and satellites.

Indeed, the situation is even worse for UBV photometry than I have represented here; for the above figures for this popular system refer only to the precision reached in comparing normal stellar spectra with one another. But the spectral energy distributions of planets are unlike those of stars, and in fact the UBV system is not well defined for many solar-system objects.

Thus, for example, we cannot place Mars on this system with more precision than a tenth of a magnitude in any band or color index of the UBV system (Young, 1974b). But normal human eyes are made to tighter tolerances than we can make UBV photometers; furthermore, the overlapping response functions of the visual pigments produce much less aliasing than do the UBV passbands. Consequently, two people with normal color vision can agree on the color of Mars much more closely than can two astronomers trying to measure it with UBV photometers.

## APPENDIX B

The FORTRAN 77 subroutine listed here converts spectral reflectances, tabulated at 10-nm intervals, into CIE chromaticity coordinates, assuming Illuminant C. The DATA statements contain the CIE 1931 color-matching functions weighted by the relative spectral radiant power distribution for Illuminant C, taken from Table I(3.3.8) of Wyszecki and Stiles (1982). These functions allow the accurate approximation of the necessary integrals by the trapezoidal rule.

Chapter 5 of MacAdam (1981) gives a very thorough discussion of various numerical methods for calculating the chromaticity coordinates (x, y) and luminance factor (Y) for a surface of known spectral reflectance. The method employed here is known in the color-science literature as the method of weighted ordinates; see also p.159 of Wyszecki and Stiles (1982).

This method was checked by Nickerson (1935), using the spectrophotometric curves of the most saturated Munsell papers of the 10 principal hues (5R, 5YR, 5Y, etc.) Fig. 1 of that paper shows that these curves have much steeper sides than the reflectance curve of any known planetary surface. Thus, the error committed in computing CIE coordinates of the saturated Munsell hues will exceed those for planets. Nickerson found that summation for 10 renotation, as described in the text. The agreement was within the accuracy of the estimates from the Munsell book.

Third, spectral reflectance data with Munsell notations and chromaticity coordinates for several paints produced by Nuodex, Inc. (Piscataway, N.J.) were provided by Dr. Dan Phillips. One of these that is very similar to the most saturated regions on Io was run through the program listed here. The computed chromaticity coordinates deviated by an average of one part in ten thousand from those computed at Nuodex. As the tabulated data extend only from 400 to 700 nm, I believe the error is non-zero because of differences in extrapolating the spectra to the full 380 - 770 nm interval.

Fourth, a crude check can be obtained by comparing the computed Io color against the observations of careful observers. Probably the most intensive visual observations of the Galilean satellites were made by Lyot and his co-workers Gentili and Camichel when they mapped the satellites at Pic du Midi (Lyot 1943, 1953). Observations were made in 1941 with a 38 cm aperture, and "With the 500 enlargement ... the satellites appeared as disks with very sharp edges and each of them could be identified very easily by its diameter, its brightness, and its color.... Io, notably larger than Europa, was more pale and of a yellowish color.... Ganymede, comparable to Io in color and

```
      SUBROUTINE CIE (REFL, X,Y,BIGY)
C  INPUT IS SPECTRAL REFLECTANCE TABLE (REFL);
C  RETURNS VALUES OF CIE CHROMATICITY COORDINATES (X, Y)
C   AND VISUAL REFLECTANCE (BIGY) FOR ILLUMINANT C.
C  REFLECTANCE DATA ARE STORED AT 1Ø NM INTERVALS, WITH
C  REFL(1)  = REFLECTANCE AT 38Ø NM, AND
C  REFL(4Ø) = REFLECTANCE AT 77Ø NM.
C
      DIMENSION XBAR(4Ø),YBAR(4Ø),ZBAR(4Ø),REFL(4Ø)
C
C   WEIGHTS INCLUDE ILLUMINANT C; SEE TABLE I(3.3.8) OF
C   WYSZECKI & STILES (1982), P.768.
C
      DATA XBAR/.ØØ4,.Ø19,.Ø85,.329,1.238,2.997,3.975,3.915,3.362,
     1 2.272,1.112,.363,.Ø52,.Ø89,.576,1.523,2.785,4.282,5.88,7.322,
     2 8.417,8.984,8.949,8.325,7.Ø7,5.3Ø9,3.693,2.349,1.361,.7Ø8,
     3 .369,.171,.Ø82,.Ø39,.Ø19,.ØØ8,.ØØ4,.ØØ2,.ØØ1,.ØØ1/
      DATA YBAR/.Ø,.Ø,.ØØ2,.ØØ9,.Ø37,.122,.262,.443,.694,1.Ø58,1.618,
     1 2.358,3.4Ø1,4.833,6.462,7.934,9.149,9.832,9.841,9.147,7.992,
     2 6.627,5.316,4.176,3.153,2.19,1.443,.886,.5Ø4,.259,.134,.Ø62,
     3 .Ø29,.Ø14,.ØØ6,.ØØ3,.ØØ2,.ØØ1,.ØØ1,Ø./
      DATA ZBAR/.Ø2,.Ø89,.4Ø4,1.57,5.949,14.628,19.938,2Ø.638,19.299,
     1 14.972,9.461,5.274,2.864,1.52,.712,.388,.195,.Ø86,.Ø39,.Ø2,
     2 .Ø16,.Ø1,.ØØ7,.ØØ2,.ØØ2,Ø.,Ø.,Ø.,Ø.,Ø.,Ø.,Ø.,Ø.,Ø.,Ø.,Ø.,Ø.,
     3 Ø.,Ø.,Ø./
      X=Ø.
      Y=Ø.
      Z=Ø.
C  USE SUMS FOR INTEGRALS.
      DO 2Ø I=1,4Ø
      X=X+REFL(I)*XBAR(I)
      Y=Y+REFL(I)*YBAR(I)
   2Ø Z=Z+REFL(I)*ZBAR(I)
      BIGY=Y
      SUM=X+Y+Z
      X=X/SUM
      Y=Y/SUM
      RETURN
      END
```

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# FIGURE CAPTIONS

Fig. 1. Spectral tristimulus values of monochromatic lights of equal power, with respect to monochromatic primaries at 700 nm (approximately a red-filtered tungsten lamp), 546.1 nm (the mercury green line), and 435.8 nm (the mercury blue line), for the CIE 1931 standard observer [see Table I(3.3.3) of Wyszecki and Stiles, 1982]. At each wavelength, the ordinates show the amounts of the three primaries required by the standard observer to match a light of that wavelength and fixed power in a two-degree field. Note that these color-matching functions for real primaries have negative lobes, as discussed in the text. Notice also that, at each primary wavelength, the curves for the other two primaries cross at zero. For example, at 546.1 nm, the green line alone matches itself, so the required amounts of the red and blue primaries are zero.

Fig. 2. The 1931 CIE color-matching functions, which refer to non-physical primaries called X, Y, and Z. Their relation to the R, G, B primaries is discussed in Section 3.3.3 of Wyszecki and Stiles (1982). Fig. 4(3.3.3) in their book shows the X, Y, Z tristimulus space; the cone containing all real colors lies entirely within the first octant of (X, Y, Z) space. Notice that all spectral colors (and hence, all real colors) have only positive tristimulus values with

respect to these non-physical primaries.

Fig. 3. Visual fundamentals, according to Smith and Pokorny (1975). The blue fundamental has been multiplied by a factor of 100, because the absolute blue sensitivity of the eye is very low.

Fig. 4. Colors of surfaces that are black at short wavelengths and perfectly reflecting at wavelengths longer than that of this reflectance step, plotted in the (hue, chroma) Munsell subspace. Selected points are labelled with the wavelength (in nanometers) at which the spectral jump occurs. The next figure shows the missing coordinate.

Fig. 5. Colors of surfaces that are black at short wavelengths and perfectly reflecting at wavelengths longer than that of this reflectance step, plotted in the (chroma, value) Munsell subspace. Selected points are labelled with the wavelength at which the spectral jump occurs. The previous figure shows the missing coordinate.

Fig. 6. Spectral reflectance curves of two similar yellow surfaces. The eye can distinguish color differences about 1/4 as large as that between these two surfaces.

Fig. 7. Planetary target colors (asterisks) and colors

actually printed (open symbols) as square patches in the text on pp. 401-402 of Young (1985). Target and actual colors for each object are connected by straight lines. The target colors were calculated from published planetary reflectance spectra, and the printed colors were determined by comparison with the Munsell Book of Color; the uncertainties in these estimates are about the size of the plotted symbols. The deviation of the symbols for each object from the target color gives some idea of the accuracy with which colors can be reproduced in careful press work, and their scatter indicates the precision of color printing. This figure shows the Munsell (hue, chroma) subspace; Fig. 8 shows the missing coordinate.

Fig. 8. Munsell (chroma, value) subspace for the colors shown in Fig. 7.

Fig. 9. Additional colors from (Young, 1985), as shown in Fig. 7; see Fig. 10 for the missing coordinate. The "Io patch" appears on p. 402 of (Young, 1985); "Io bottom" refers to the most saturated portion of the Io picture at the bottom of p. 400. The "Moon photo" (filled symbols) is on p. 399, and the "Moon patch" (open symbols) is on p. 401. "Mars soil" refers to the picture at the top of p. 401.

Fig. 10. Munsell (chroma, value) subspace for the colors shown in Fig. 9.

Fig. 11. Additional colors from (Young, 1985), as shown in Fig. 7; see Fig. 12 for the missing coordinate. "Io top" is a saturated area in the picture at the top of p. 400 of (Young, 1985); "Belt" and "Zone" refer to the lower-contrast panel of the Jupiter picture on p.402. Note that the contrast of this picture is still unrealistically high: the belt was reproduced with nearly 3 times more chroma and much redder than spectrophotometry of Jupiter indicates. The true color of belts on Jupiter is very similar to the average color of Io, but slightly redder (i.e., nearly the same hue as the Io picture at the top of p. 400, but with about half the chroma of the most saturated areas in that picture).

Fig. 12. Munsell (chroma, value) subspace for the colors shown in Fig. 11.

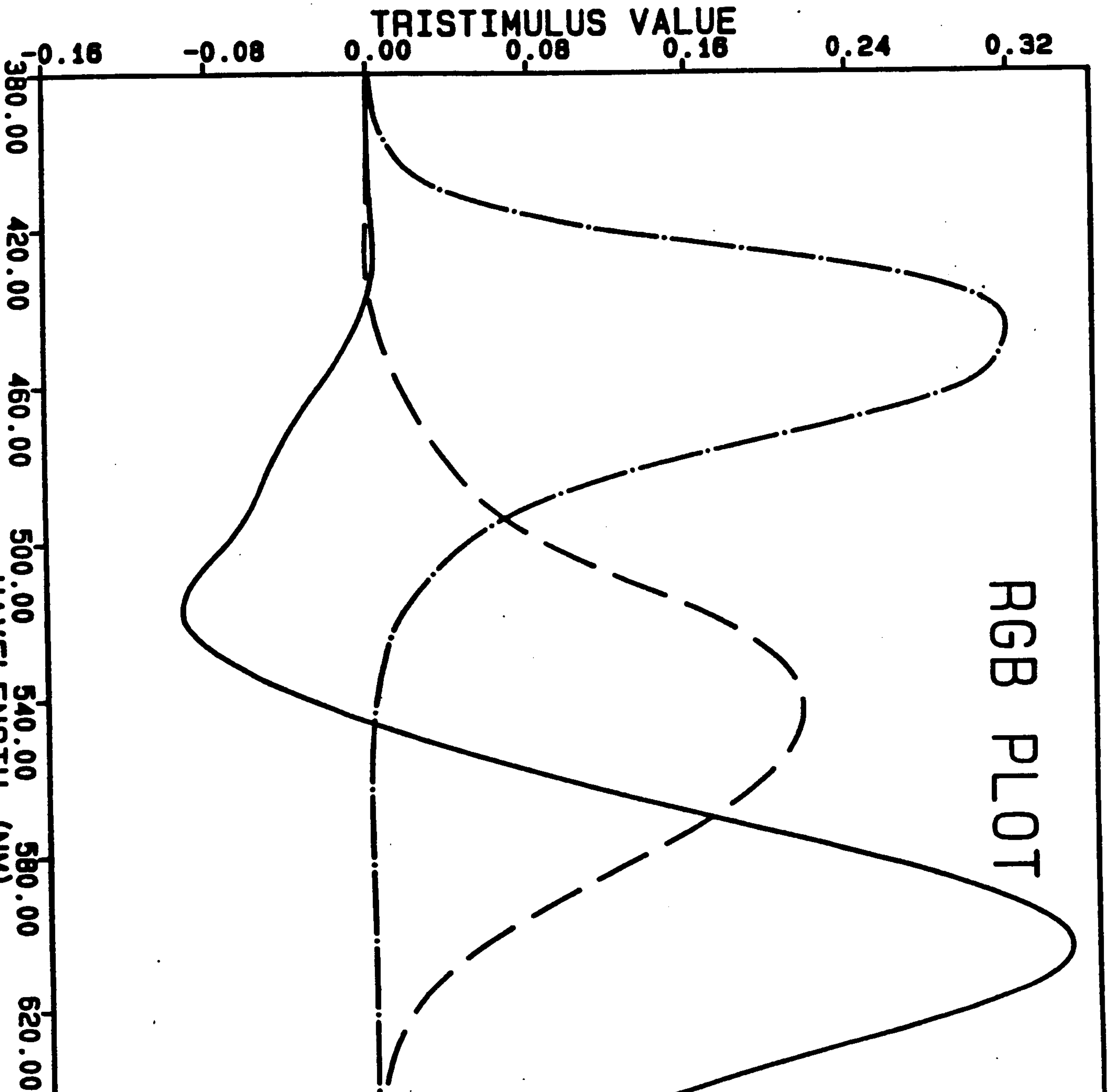



Fig. 1

88/03/11. 11.57.45. QT00145

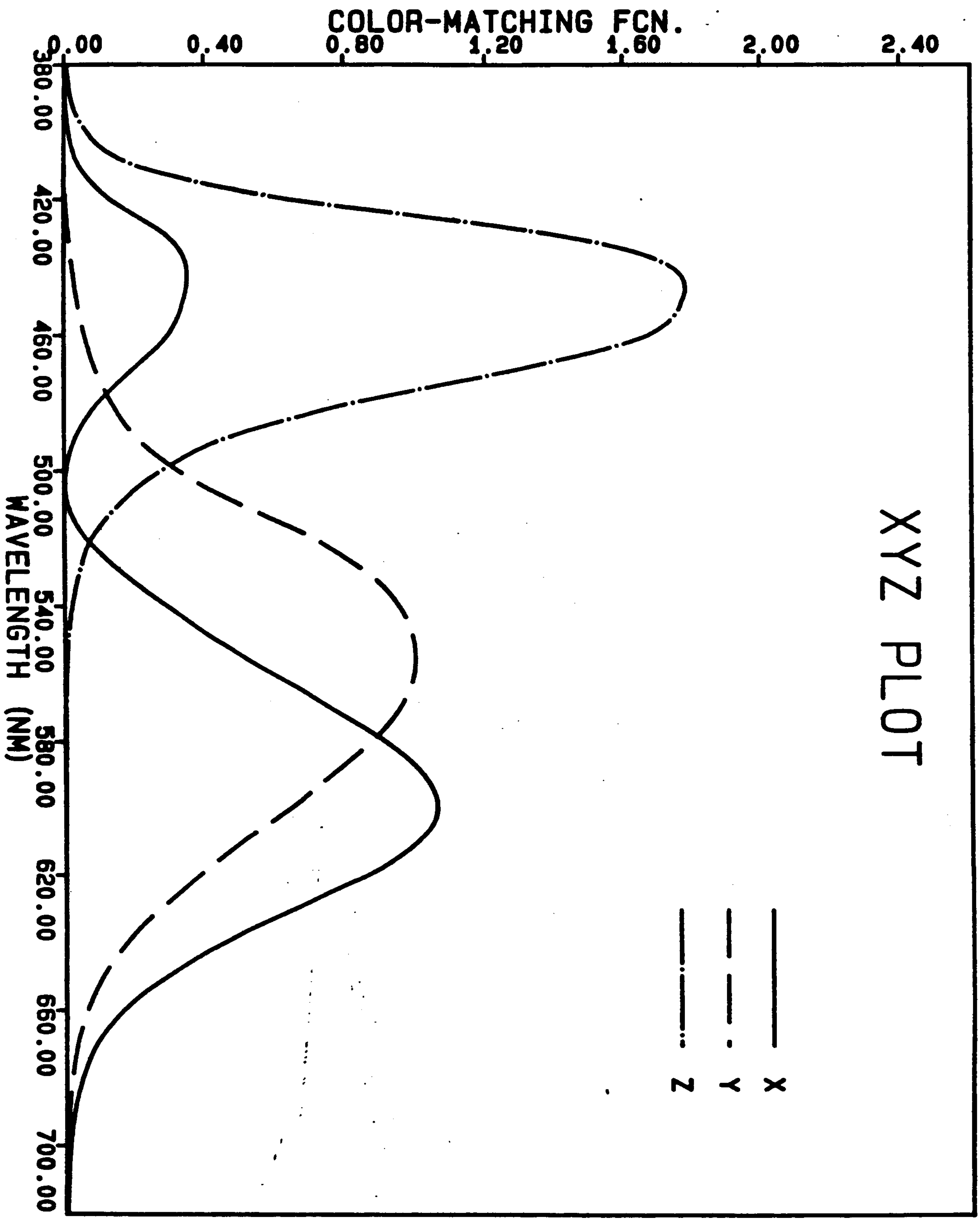



Fig. 2

88/03/11. 11.55.48. QT00145

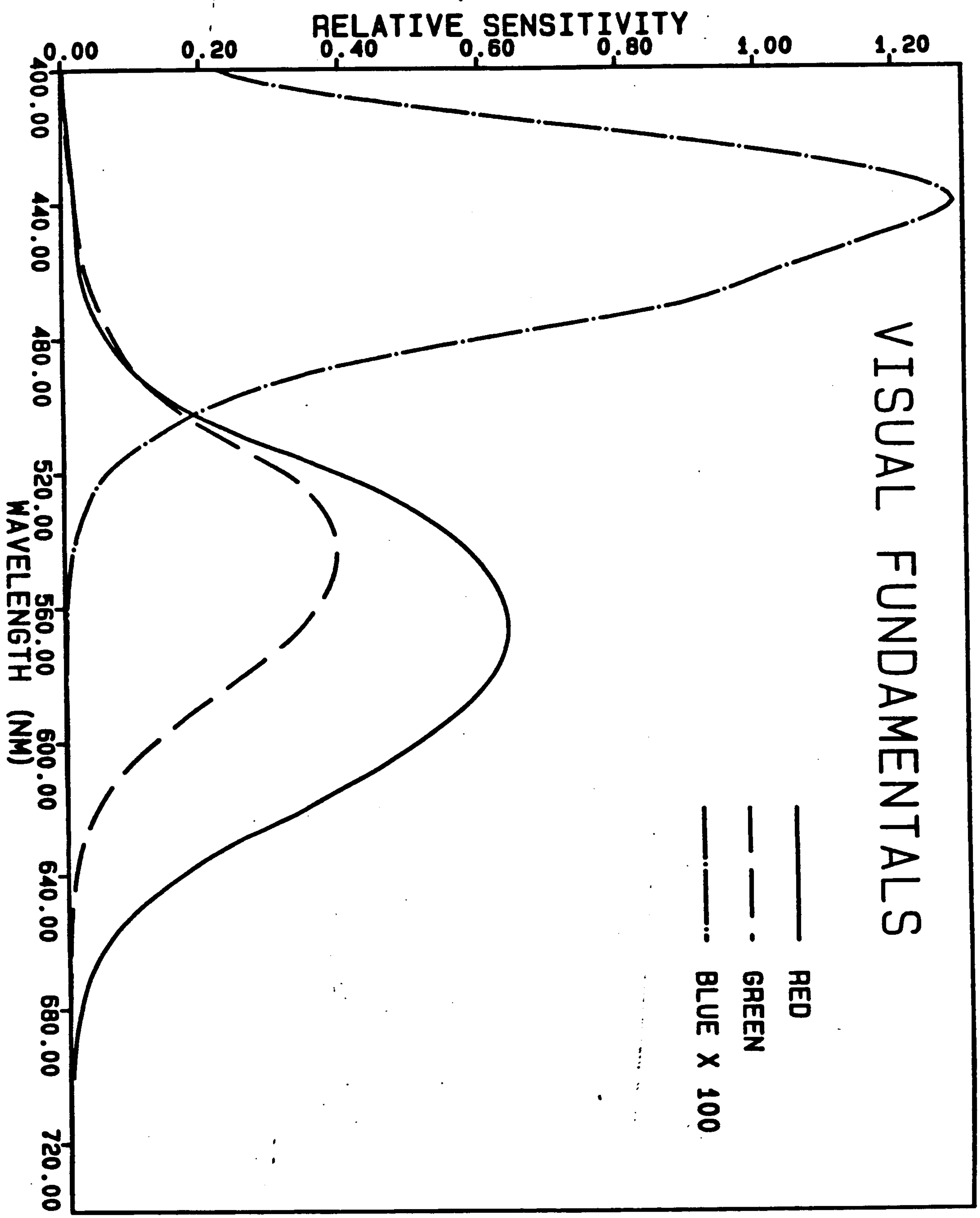



Fig. 3

88/03/10. 11.21.52. QT00145

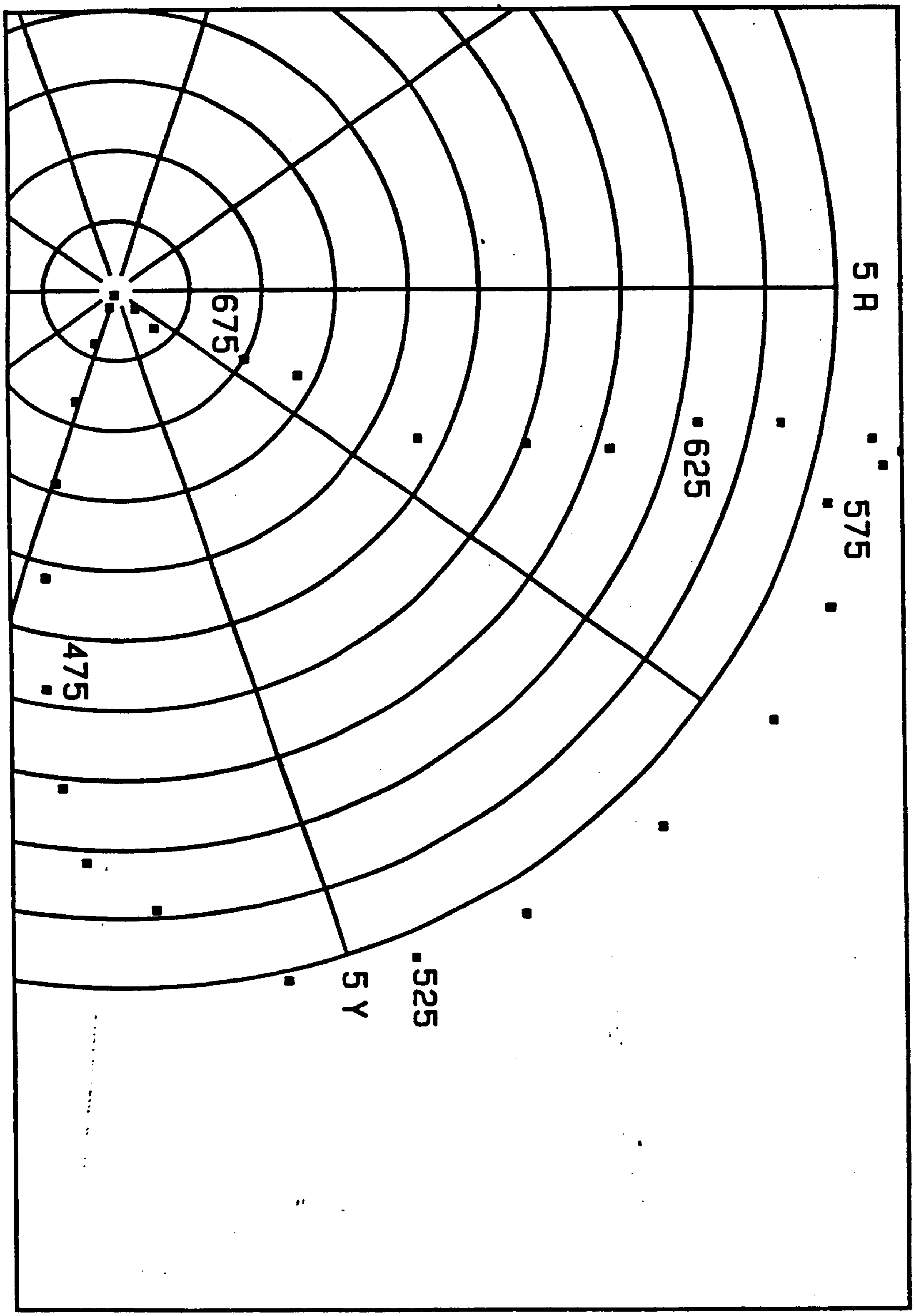



Fig. 41

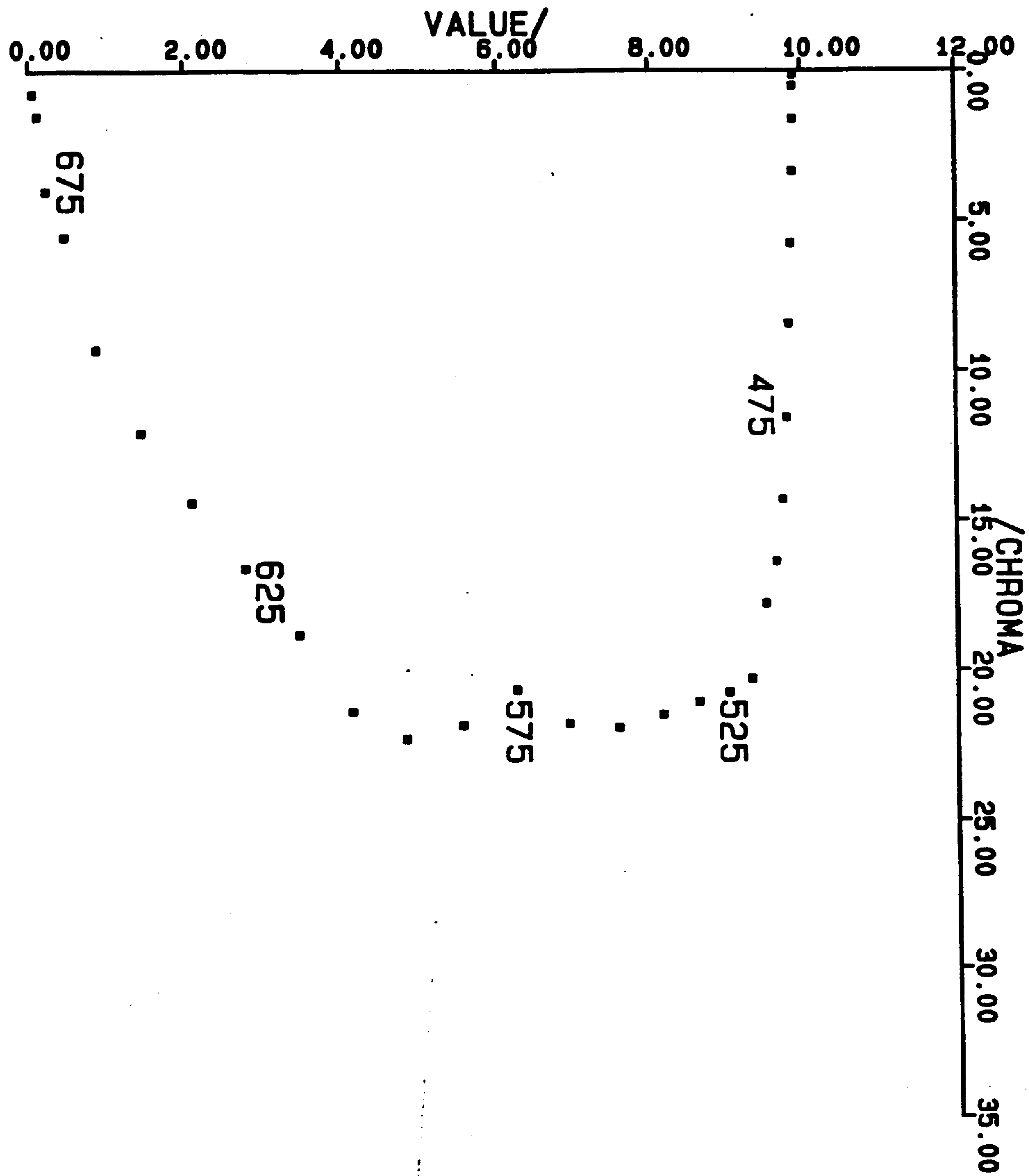



Fig. 5

88/03/11. 12.06.32. QT00145

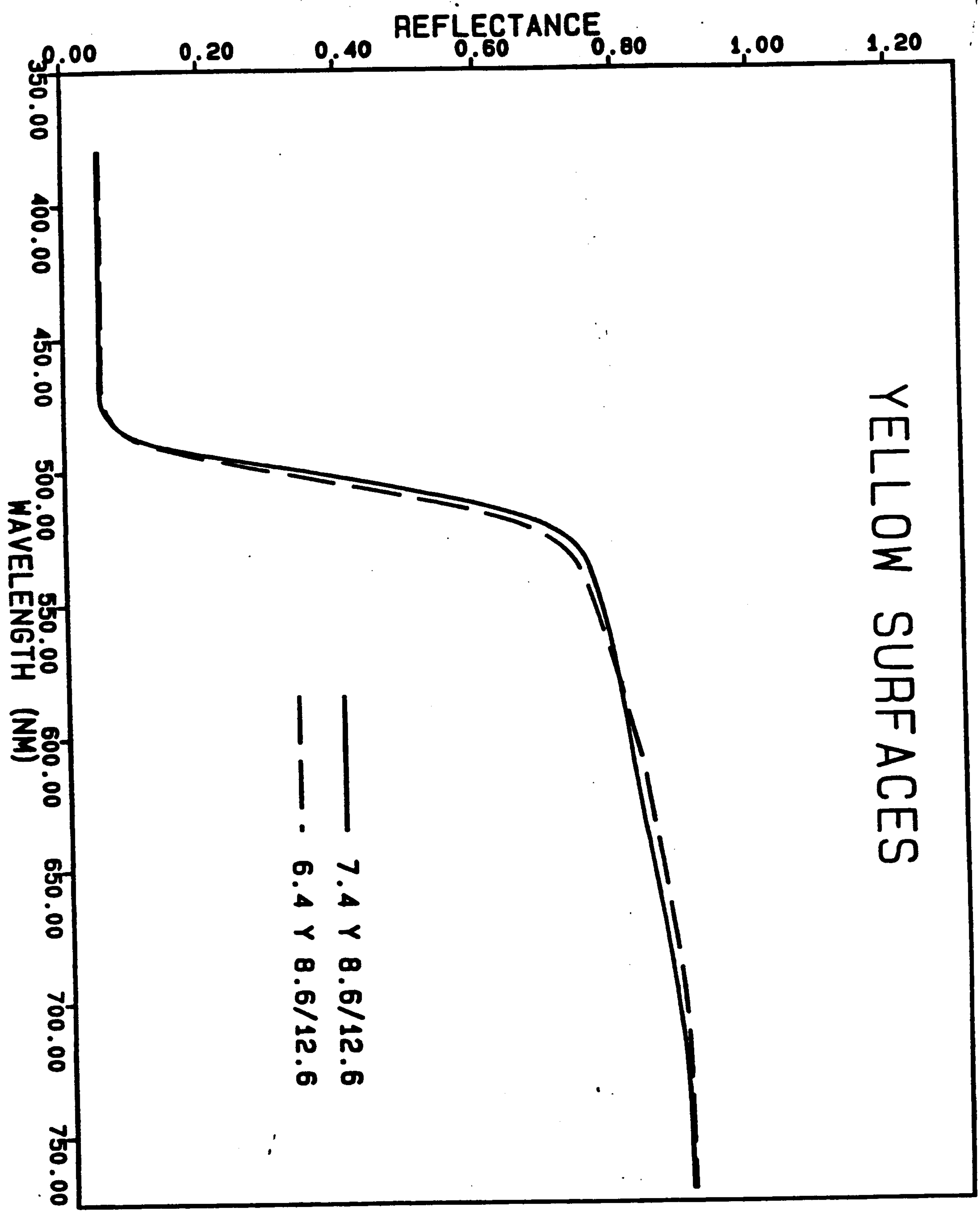



Fig. 6

88/03/16. 11.44.38. QT00145

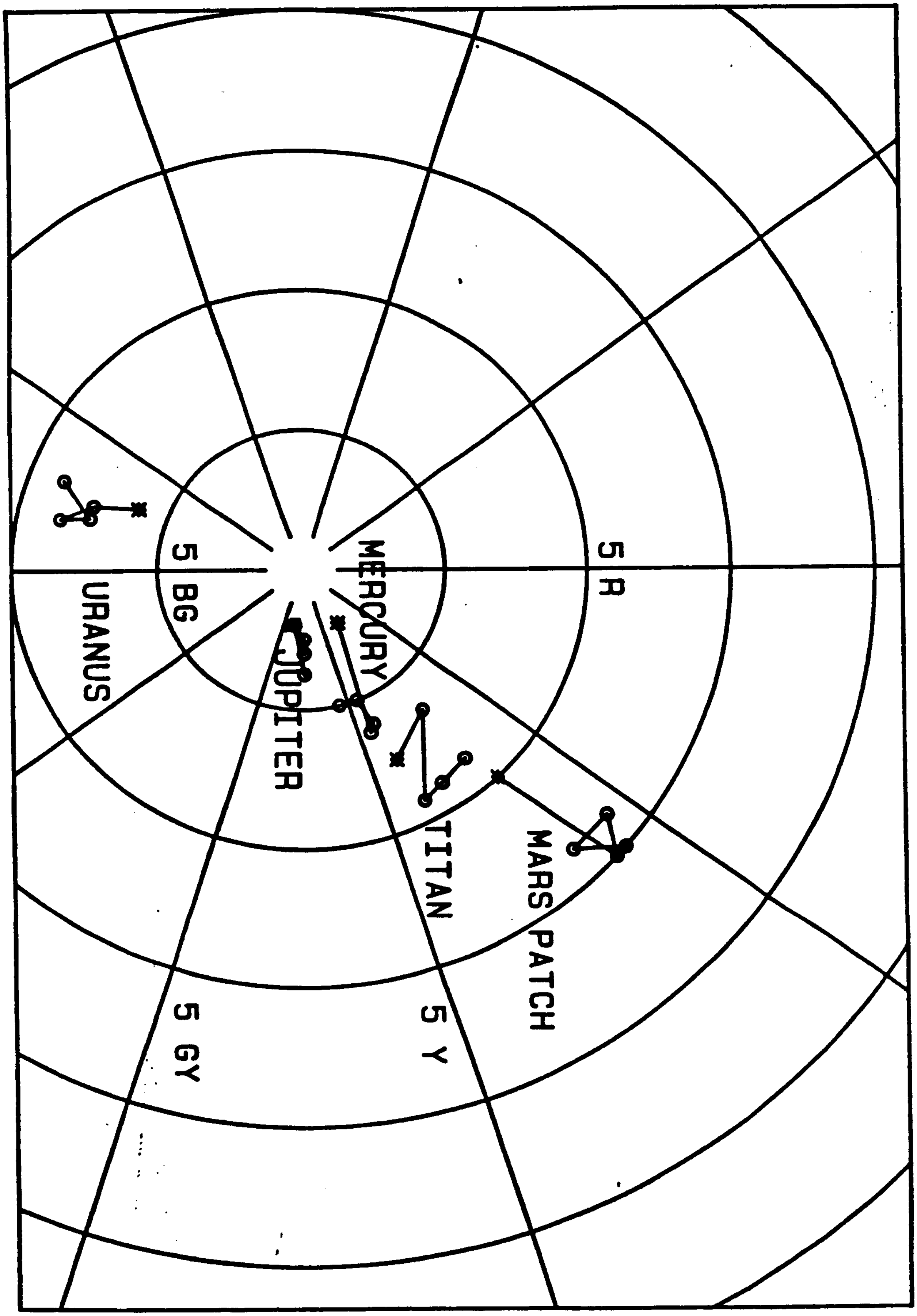



Fig. 7

88/03/11. 12.02.50. QT00145

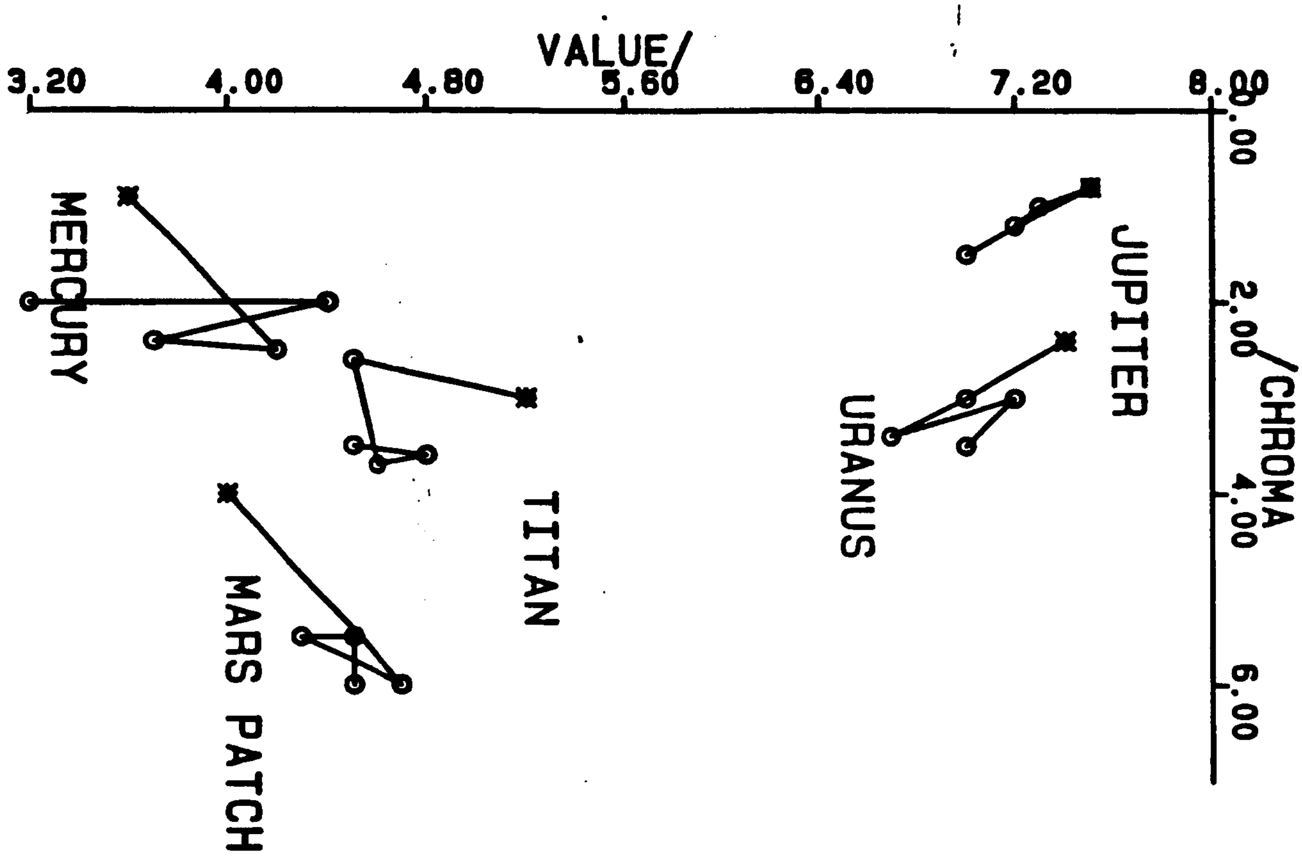



Fig. 8

88/03/11. 12.02.51. QT00145

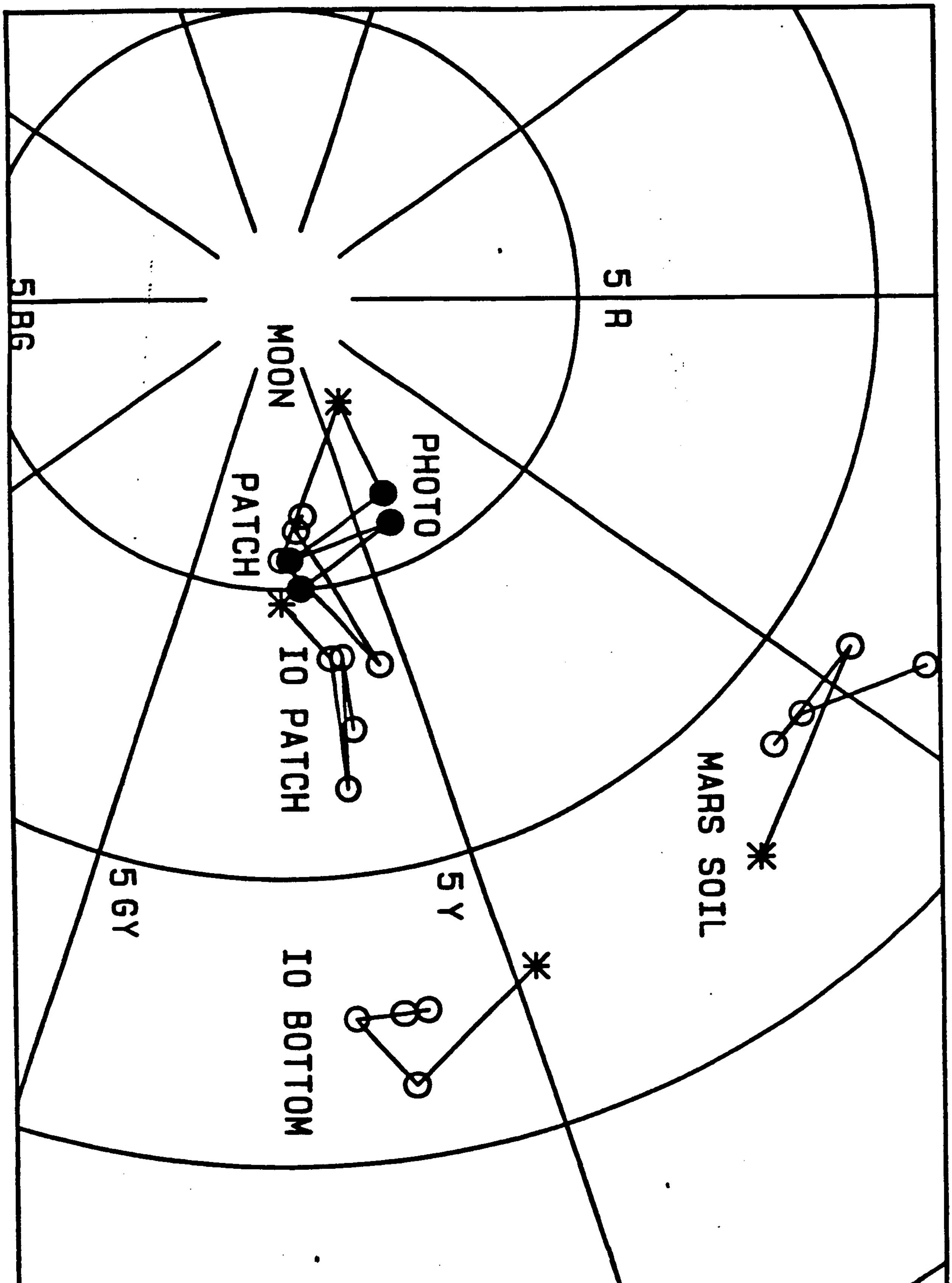



Fig. 9

88/03/11.    12.02.52.    QT00145

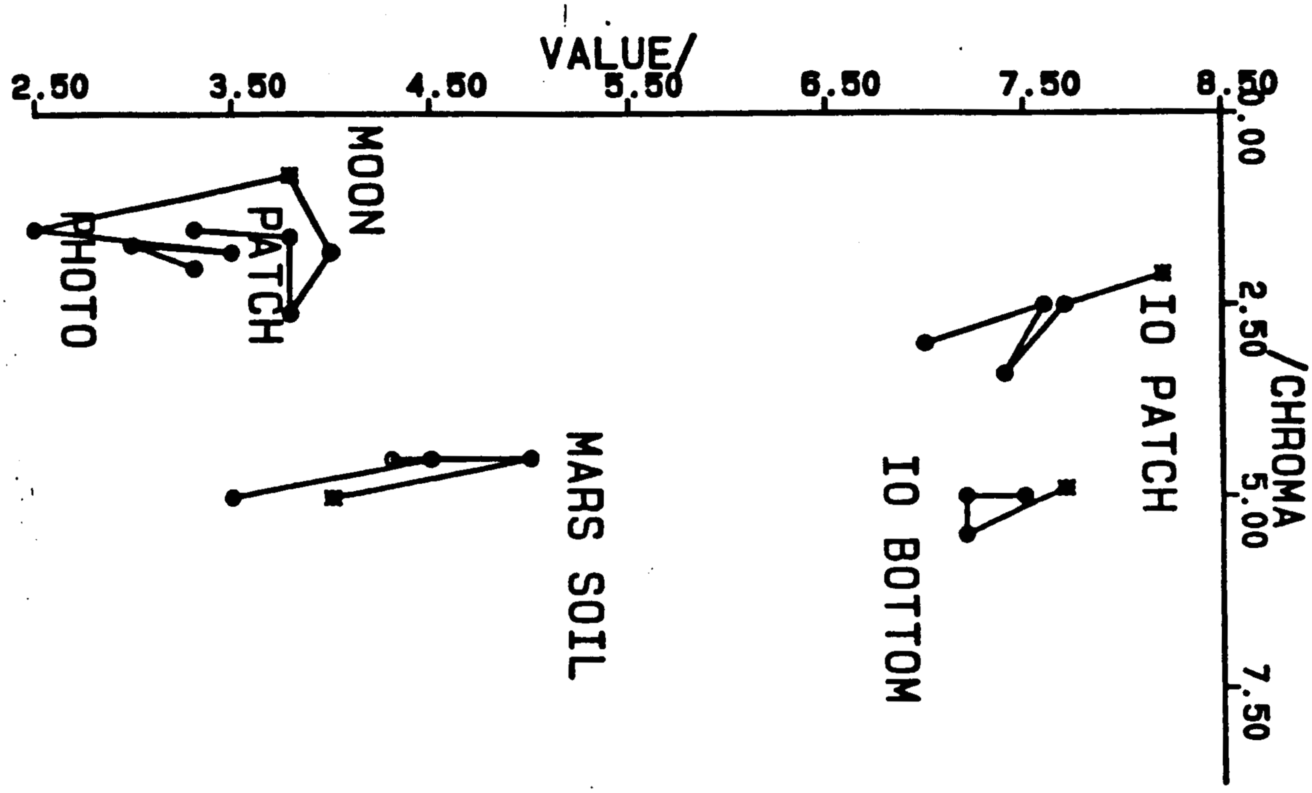



Fig. 10

88/03/11.    12.03.44.    QT00145

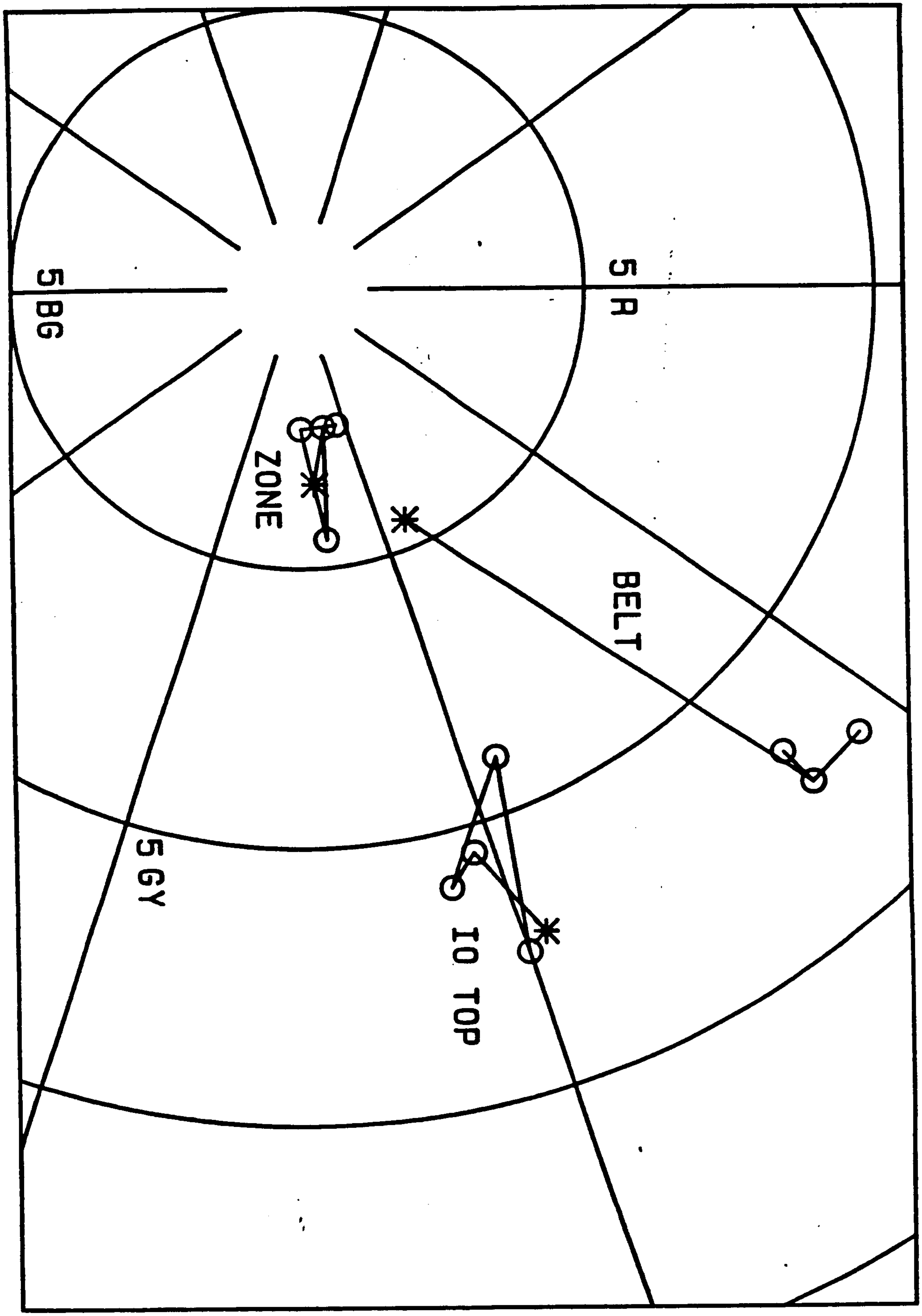
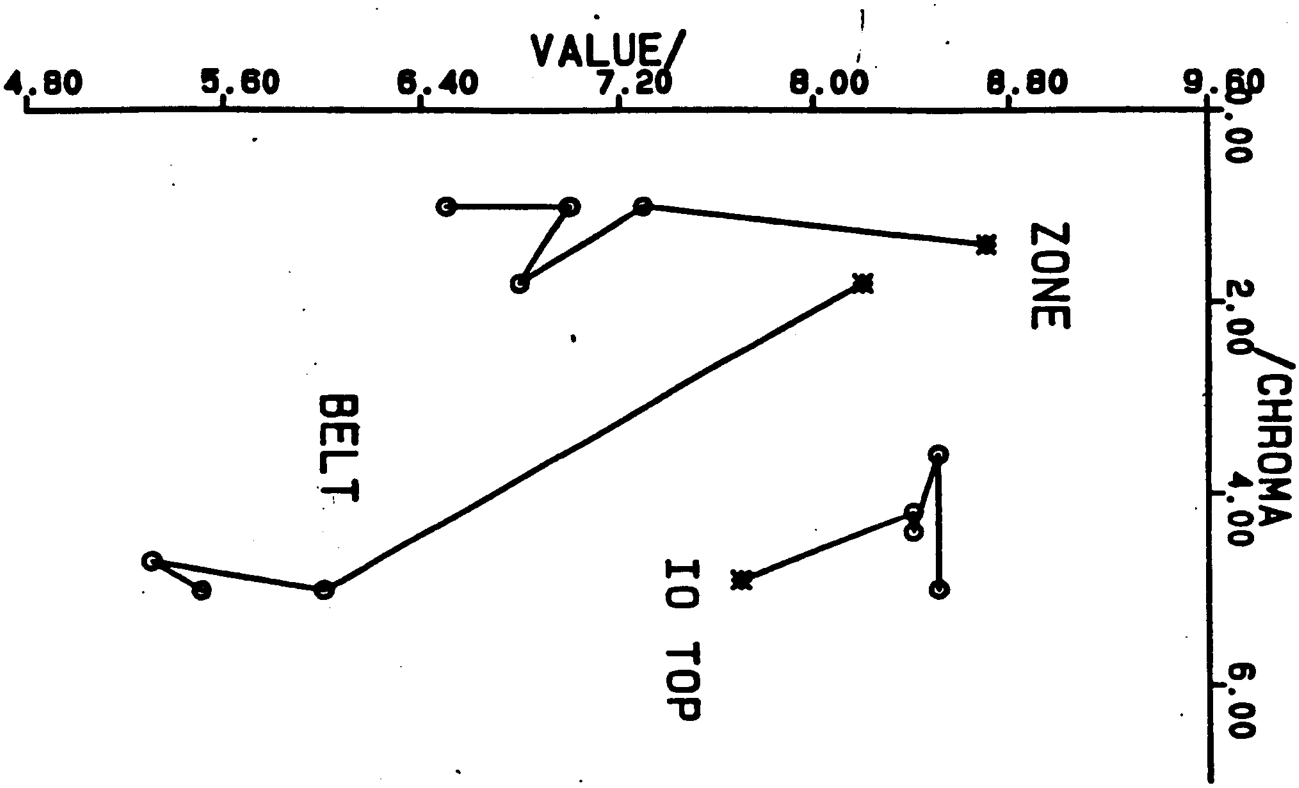



Fig. 11

88/03/11. 12.03.46. QT00145




88/03/11. 12.03.48. QT00145

Fig-12