The Electronic Computer as an Astronomical Instrument

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SUMMARY

The enormous potential of the electronic computer as an instrument of observational and theoretical research is emphasized. Astronomical examples are used to illustrate the concept of programming and the flexibility of electronic computers. Specific recommendations are made for the effective use of these devices in astronomy.

1. INTRODUCTION

THERE are very few astronomers fortunate enough to work with paper and pencil alone. For most of us, there is a long path to be followed, from observations to conclusions, or from theory to prediction, before our work can be useful to ourselves and others. In some cases the data obtained in one night of observations may take weeks to analyse. This process may be so time-consuming that frequently only a fraction of the data are reduced before the astronomer is diverted by new problems. As a result much useful information gathers dust and never appears in the literature.

What can be more detrimental to astronomical enthusiasm than routine, dull, laborious computation! It has strangled some large programmes, it has delayed others and it frequently drives promising graduate students completely away from astronomy. Unless a large force of desk calculator operators is available (and this is unlikely when astronomers must hire assistants in competition with industry), the astronomer must do the work himself and spend valuable hours at menial tasks, instead of in creative thought.

With this obstacle in the path, one would think that astronomers would leap at the prospect of using high-speed computers. This has not been the case. (Astronomers are innately as conservative a group of scientists as one can find.) With the exception of a few widely dissimilar fields the use of computers has been timid and sporadic.

By and large, the principal reason has been inertia. Astronomers are vaguely aware of what electronic computers can do to help them, but few have taken the trouble to investigate further. For some reason, electronic machines are regarded either as mysterious or difficult to learn to use. In reality, with a little guidance, anyone familiar with desk calculators can be producing useful results with a high-speed machine in a matter of six weeks or less. While this may appear to be a long time to devote to learning a new technique, it is an investment which saves far more time in the end.

Naturally, astronomers cannot be expected to change their methods overnight. It will be the young astronomer, accustomed to learning new things, who will accept electronic computation in his stride. It is to these men, especially, that this article is addressed.

2. Simple Examples of Computer Techniques

Before discussing specific astronomical applications, let us examine the electronic computer in more detail. It has five principal parts: the input, into which information if fed; the output, out of which results eventually come; the memory, where information is retained for use during the computation; the arithmetic unit, in which the calculation is performed; and the control unit, which supervises the entire operation.

Each machine has a basic vocabulary of instructions which it is able to perform. These are the "words" of the "machine language". By assembling these instructions in the proper sequence, a series of operations can be performed on the data to solve a specific problem. This sequence is called the "programme" and the process of constructing it is called "programming". The instructions of the programme must be written in a (usually numerical) code that the machine can understand. This process is called "coding".

Once the correct sequence has been constructed for a particular problem, it can be used again and again on different data. For example, once a programme for reducing photoelectric observations has been written and coded for a particular type of computer, it can be used without further programming, to reduce as much data as desired. It can also be used on any similar machine anywhere in the world.

In practice, the entire programme is stored in the memory. Once the execution of the programme is begun it continues automatically. After the calculation has been completed for one set of data, the results are punched or printed, and new data are automatically fed in.

The programme *library* is one of the most important features of any computer installation. Programmes of general interest have been developed for all the standard machines and many of them have astronomical applications. For example, least-squares curve fitting programmes are available, and to use them it is only necessary to punch the data on cards or tape in the proper form. Standard procedures of interpolation, quadrature, and many statistical operations are already available and can be used by astronomers with very little additional work.

Purely astronomical applications, however, will have to be programmed by the astronomers themselves. If they wait for someone else to do it, it will never be done.

Fortunately, many techniques are being developed to make programming as simple as possible. The tendency is toward making the machine do most of the work. While the professional programmer regards these short-cuts with some disdain, the beginner would do well to learn them. Although programmes written by these methods may not make the most efficient use of the machine, they lead to workable error-free programmes in a much shorter time.

One such approach is called "automatic programming" and a typical example is FORTRAN, developed by IBM for its Type 704 computer. FORTRAN is very attractive to the scientists because programming is done in a language very similar to algebra. For example,

```
Y = (A**2)+(B**2)
  - (2.*A*B*COSF (THETA))
```

is the FORTRAN equivalent of evaluating:

$$y = a^2 + b^2 - 2ab\cos\theta$$

A single asterisk indicates multiplication, a double asterisk is exponentation, and COSF indicates that the cosine function of the argument THETA is desired.

When FORTRAN is used, the entire programme is written in FORTRAN language and fed into the machine. The computer itself then decides how to express the FORTRAN programme in its own basic code and produces a deck of cards which can be used in the future to run the problem with appropriate data.

"Interpretive systems" are also widely used. Here we substitute a simpler and more versatile language for the one built into the machine, and have the machine "translate" each instruction immediately before executing it. A typical interpretive code is the one developed at Bell Telephone Laboratories for the IBM Type 650.[1] The example, given above, now is expressed by the following series of instructions:

3	201	201	601
3	202	202	602
0	304	203	603
3	603	201	604
3	604	202	605
1	601	602	606
2	606	603	607

This appears to have little relation to the formula it is intended to represent, but we will soon see that it is entirely logical. (Although not programmed as efficiently as possible, this will serve as a suitable example.)

Each line represents one instruction and each instruction consists of 10 digits: first one digit, then three groups of three. To understand this programme it is necessary to know a little about the memory unit used by this system. It consists of one thousand locations, with "addresses" 000 to 999. In each location one 10-digit word can be stored.

Information can be sent to or from any location by specifying its address at an appropriate place in an instruction. When new information is sent to a particular location the old information is automatically erased; but information can be called for from any location without affecting the information stored there. That is, when we send information to location 601, the number previously in 601 is lost; but when we call for information from 601, the number in 601 remains there. Prior to executing the instructions given above, we will assume that a, b, and θ have been stored in locations 201, 202 and 203 respectively.

The first instruction reads

3 201 201 601

The first digit, 3, indicates that a multiplication is to be performed. The multiplier is in 201, the multiplicand is also in 201, and the product is to be stored in 601. The instruction, therefore, computes a^2 and stores the result in 601.

In a similar way, the second instruction computes b^2.

The interpretation of the third instruction is somewhat different. Since the first digit is zero, it indicates that the first group of three digits is not an address, the way it was in the previous instructions, but instead is an instruction code. In this case, 304 indicates that the cosine of the number in location 203 is to be taken and

[1] IBM Technical Newsletter No. 11.

stored in 603. This is multiplied by a in the next instruction and stored in 604; and by b in the next and stored in 605.

Finally, once we know that the code "1" is addition, and "2" is subtraction, the last instructions should be easily understood. The final result can be found in location 607.

By way of contrast, consider the programme for the same calculation using a system called SOAP on the IBM Type 650:

```
BEGIN   RAU   A
        MPY   A
        STU   ASQ
        RAU   B
        MPY   B
        STU   BSQ
        RAU   THETA
        LDD             COS
        MPY   A
        RAU   8003
        MPY   B
        STU   TEMP
        RAU   ASQ
        AUP   BSQ
        SUP   TEMP
        STU   Y         END
```

Note how much more has to be written in comparison with either FORTRAN or the Bell interpretive system. This is a very flexible programming procedure, but it is also somewhat complicated.

Without going into much detail, a few things can be pointed out. Every instruction begins with a three-letter mnemonic code. Memory locations are also given symbolic codes. The first three instructions calculate and store a^2. RAU means Reset Add Upper accumulator (part of the arithmetic unit). The effect is to clear the arithmetic unit and set up the multiplier, a. The second instruction carries out multiplication by a; the third instruction, STU, means STore Upper accummulator, and it stores the product in the symbolic location ASQ. To explain the rest of this programme is beyond the scope of this article.

Brief though our description has been, it should at least indicate that using a technique such as FORTRAN, or the Bell Laboratories interpretive code, is not beyond the capabilities of any astronomer.

3. THE ROUTINE USE OF COMPUTERS

Suppose we have become reasonably proficient programmers; what then? To what sort of problems could this technique be applied? To begin with one could automatize all the standard computations that are being done at an observatory: radial velocities, photoelectric reductions, least squares solutions, plate reductions, radio telescope reductions, statistical analyses, etc.

The process begins by making a broad outline of the computation in the form of a "flow diagram". The entire computation is divided into "boxes"; each box represents a separate phase of the problem, frequently complete within itself. The boxes are linked by flow lines which indicate the path the computation should follow. The machine can be instructed to choose between alternate paths; for example, different procedures may be needed depending upon the sign of a result, or perhaps a particular function is best represented by one expansion for large values of the argument and another for small values. The computer can be programmed to make decisions of this kind.

The problem is usually programmed one box at a time. Each large box may be further subdivided into smaller boxes, depending upon its complexity. By using a flow diagram, the programming can be done in an orderly way and the interrelation of all the parts is clearly visible. In explaining a problem to someone else, either an astronomer or a computer expert, it is much easier to talk in terms of the flow diagram than in terms of the programme. The programme is cluttered with details of little interest to anyone but the programmer, but a properly prepared flow diagram gives the essence of the calculation.

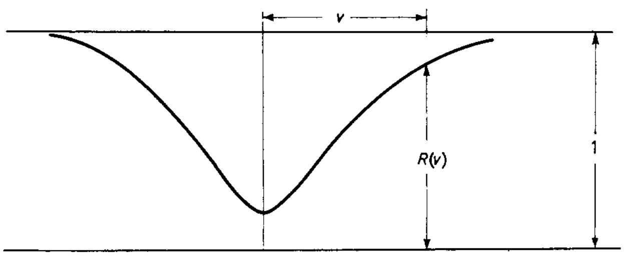

FIG. 1. Definitions for line profile computation.

Consider the following example from the theory of absorption lines. Suppose we want to find the profiles of lines formed by scattering according to the SCHUSTER-SCHWARZSCHILD model. The parameters of the problem are:

(1) the abundance factor, τ_0;
(2) the limb darkening, $I^{(0)}/I^{(1)}$; and
(3) the damping, a.

The line profile is built up point by point using the variable, v, to measure the distance from the centre of the line. The object of the calculation is to compute $R(v)$, the residual intensity at the point, v, in units of the continuum (Fig. 1).

CHANDRASEKHAR[2] has given the solution for $R(v)$, and is has been written for purposes of computation[3] as

$$R = \frac{\frac{4}{3} + Ky}{\frac{4}{3} + \tau_1 + 2y}$$

where y is tabulated as a function of $e^{-\tau_1}$, and

$$K = \frac{4}{3I^{(0)}/I^{(1)} + 2}$$

depends only on the limb darkening.

[2] CHANDRASEKHAR, S., and ELBERT, DONNA in *Ap. J.*, **115**, 269, 1952.

[3] WRUBEL, M. H. in *Ap. J.*, **119**, 51, 1954.

The quantity τ_1 depends upon a, v, and τ_0, and can be found from the theory of the absorption coefficient. It is given by the relation

$$\tau_1(a, v) = \tau_0 H(a, v).$$

HARRIS[4] has tabulated the functions $H_i(v)$, necessary to evaluate

$$H(a, v) = \sum_{i=0}^{4} a^i H_i(v).$$

We have given above everything necessary to compute profiles, but we have not put things in a logical order for computation. Obviously y must be known before we can find R, and τ_1 must be known before we can find y.

The flow diagram of Fig. 2 indicates the order in which the calculations must be carried out to compute a line profile automatically. The term "Read" means that

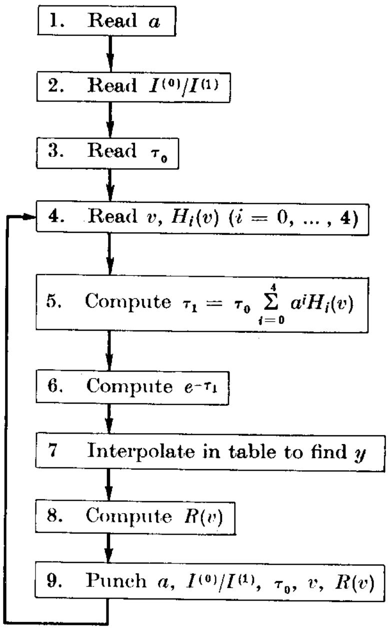

FIG. 2. Flow diagram for SCHUSTER-SCHWARZSCHILD model line profiles.

a card enters the input, and the information punched on the card is stored in the memory unit. (In box 4 the values of v and H_0 to H_4 are all on one card.) "Punch" means the results, and some identifying information are punched on a card by the output unit.

After the result has been calculated and punched for one value of v, the machine automatically reads the next value. This process continues until the last value of v is read. It is then possible to read new values of a, $I^{(0)}/I^{(1)}$, or τ_0, if desired.

As another example, consider the reduction of photoelectric observations. One procedure has been programmed for the IBM 650 by EDWARD C. OLSON for the National Astronomical Observatory, following a method due to HAROLD L. JOHNSON.

In order to reduce observations to the U, B, V, system, it is necessary to obtain

[4] HARRIS, D. L., III; in *Ap. J.*, **108**, 112, 1948.

the extinction of the atmosphere and the transformation of the instrumental colour system to the standard system.

For example, assume that the B-V colour is related to the instrumental yellow colour outside the atmosphere, C_y, by the linear transformation:

$$B-V = A_1+A_2C_y.$$

C_y is found from the raw colour, C_{y0}, by using an extinction coefficient to remove the effect of the atmosphere:

$$C_y = \frac{C_{y0}-k_1 \sec z}{1+0{\cdot}032 \sec z}$$

In turn, the raw colour is found from the yellow and blue deflections, Y^1 and B^1, together with the amplifier-gain step-calibrations, S_Y and S_B:

$$C_{y_0} = 2{\cdot}5 \log (Y^1/B^1) = S_B - S_Y.$$

If four or more standard stars of known B–V are observed, the values of A_1, A_2 and k_1, can be found by least squares. This will involve setting up three linear normal equations which are solved simultaneously by standard procedures. The flow diagram is given in Fig. 3.

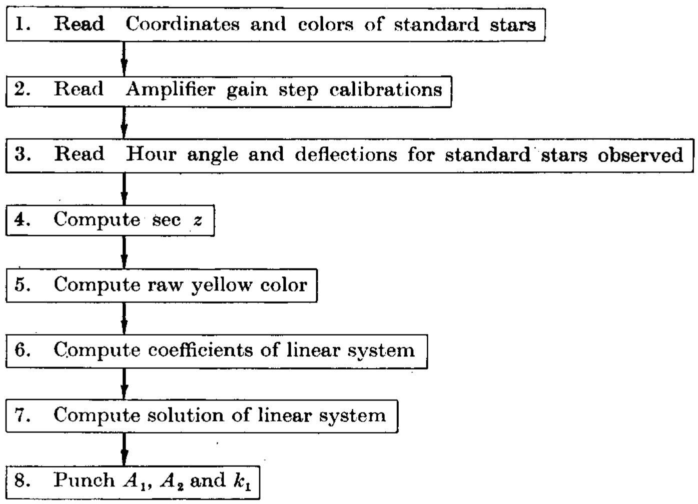

FIG. 3. Flow diagram for obtaining B–V transformation and extinction factors.

A similar procedure is used to obtain the constants needed to go from ultra and yellow deflections to U–B and V. The individual formulae are somewhat different, but eventually the problem reduces to the solution of a system of simultaneous linear equations. This suggests that we can use the same programme for solving each linear system. Box 7 can therefore be removed from the general flow of the problem and treated separately, as a "subroutine". Whenever we need to solve a linear system, we execute the subroutine. When the solution is found, the normal flow of the computation is resumed.

A flow diagram for computing the three groups of transformation coefficients is given in Fig. 4.

The main flow is interrupted three times to execute the same subroutine—each time, of course, with different data.

I do not mean to minimize the steps that lie between the flow diagram and the final programme, but the flow diagram is half the battle. With the aid of a flow diagram, the astronomer should be able to describe his computation to the programmer. If the astronomer knows programming as well, the battle is won.

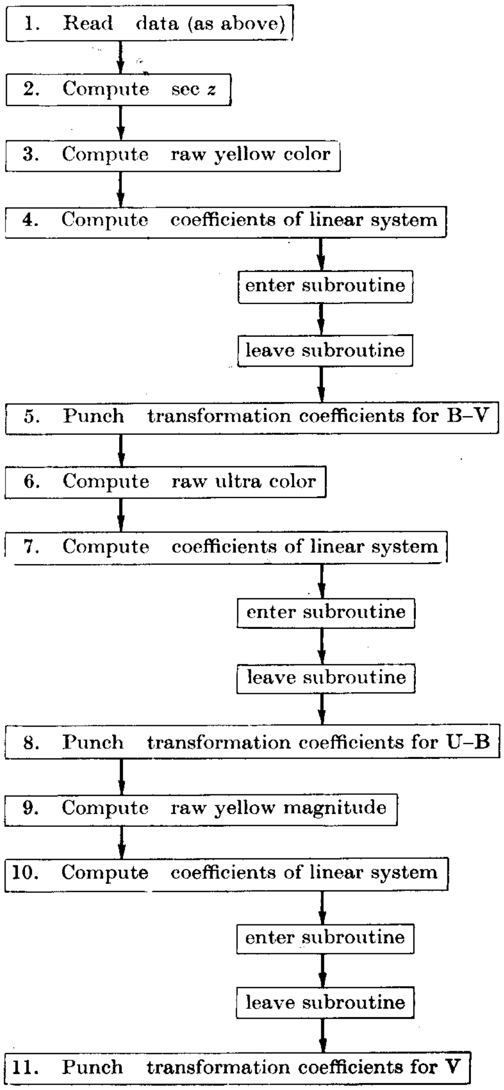

FIG. 4.

4. THE IMAGINATIVE USE OF COMPUTERS

If electronic computers did nothing but the routine reductions associated with an observatory, they would be very useful. But their potential is far greater than that. As one becomes more familiar with computers, they illuminate new ways of approaching old problems; and, which is certainly more important, they bring observational and theoretical problems that were at one time beyond our reach into the realm of possibility. For example, sequences of stellar models describing tracks of evolution in the H–R diagram require such an enormous amount of computation that high-speed machines are absolutely necessary to calculate them in a reasonable time.

To show how a simple problem can grow in generality when an electronic computer is available, consider the flow diagram of Fig. 2 again. This was a scheme for calculating line profiles according to the Schuster-Schwarzschild model. If we examine it closely, however, we see that it can be described in more general terms (Fig. 5).

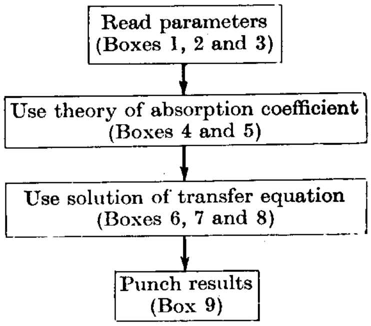

FIG. 5.

In our original application we used the results of the solution of the transfer problem for the SCHUSTER-SCHWARZSCHILD model in boxes 6, 7 and 8. We could easily substitute the solution for the MILNE-EDDINGTON model, keeping the programme for boxes 1 to 5 and box 9 intact; or we could substitute any other assumed relation between the residual intensity and the parameters.

We could further change boxes 4 and 5 if some other theory of the absorption coefficient were preferable—say, in considering the Stark broadening of hydrogen lines. In this way we may "ring the changes" on an existing programme, preserving or replacing sections as the situation demands.

Actually, electronic computers make it feasible to go beyond idealized models in which the parameters are constant with depth, to compute line profiles for model atmospheres in which ionization, damping, etc., vary with depth. Although this is possible with desk calculators as well by using weight functions or similar techniques, the ease with which these computations can be carried out on an electronic machine makes it reasonable to explore a much wider range of possibilities. For example, it would be possible to perform numerical experiments on the effect of blending or blanketing.

This flexibility of programmes is not restricted to theoretical problems. In the example we discussed concerning the reduction of observations of standard stars to obtain extinction and colour system transformations, we assumed a linear relation between the instrumental and B–V colours. This assumes the systems are not very different; but if they were, the machine could be programmed to include non-linear terms as well.

Astronomers have scarcely begun to explore the possibilities of existing computing equipment, but we might mention some of the advances that probably lie ahead.

One particularly promising application of computer techniques is in selecting, from a large memory, information which fits particular requirements. If a suitable device is perfected to transcribe a printed page directly to magnetic tape, it would become practical to record volumes of information, such as the Henry Draper Catalogue, in a form machines can easily use. This could simplify the planning of observing programmes, because it would then be possible to ask the machine to "find the co-ordinates of all A stars brighter than 10th magnitude that can be observed from McDonald Observatory in March".

Going one step further, it may one day be possible to search the literature by machine to find all references to a particular object. And, of course, there is the possibility of translation by machine, an El Dorado so many are seeking, and which will be of profit to the astronomer as well as every other scientist when found.

5. Conclusions and Recommendations

Few observatories have enough routine reductions to keep a high-speed machine busy, even for an 8-hour day. Therefore, if they do not have a theoretical department interested in machine computations they cannot justify the rental or purchase of a large calculator. Observatories connected with universities may be fortunate in having a computer facility accessible on the campus which they can share with other departments. In other cases, nearby industrial installations may be generous in offering computing time in the wee hours of the morning. (This should not disturb an astronomer.)

The success of the connection between an observatory and an electronic computer will largely depend upon the accessibility of the machine. It must be near enough so that it can be used without spending a disproportionate amount of time getting to it. It ought to be a machine for which a large programme library of standard methods is already available. (This is the case for most of the widely distributed machines and also for a few "one of a kind" machines at active research installations.) The observatory should hire a part-time programmer who would be responsible for co-ordinating the observatory's use of the machine. He would also have the responsibility of running the programmes on the machine.

Finally, at least one astronomer on the observatory staff should acquire, through experience, a knowledge of machine techniques. Otherwise, the connection between the observatory and the computer will be too remote to be effective.

The electronic computer is an important research tool. Now it is up to the astronomer to use it.