The regulation and function of the helix-loop-helix gene, asense, in Drosophila neural precursors

Andrew P. Jarman, Michael Brand*, Lily Y. Jan and Yuh Nung Jan

Howard Hughes Medical Institute, and Departments of Physiology and Biochemistry, University of California, San Francisco, San Francisco, California 94143-0724, USA

*Present address: Max-Planck-Institut für Entwicklungsbiologie, Spemannstrasse 35/3, 7400 Tübingen, Germany

SUMMARY

asense is a member of the achaete-scute complex (AS-C) of helix-loop-helix genes involved in Drosophila neurogenesis. Unlike the other AS-C members, which are expressed in subsets of the ectodermal areas (proneural clusters) that give rise to neural precursors, asense is one of a number of genes that are specifically expressed in the neural precursors themselves (the neural precursor genes). We have identified a mutant asense phenotype that may reflect this later expression pattern. As a step in understanding the determination of neural precursors from the proneural clusters, we have investigated the potential role of the AS-C products as direct transcriptional activators of neural precursor genes by analysing the regulation of asense. Using genomic rescues and asense–lacZ fusion genes, the neural precursor regulatory element has been identified. We show that this element contains binding sites for AS-C/daughterless heterodimers. Deletion of these sites reduces the expression from the fusion gene, but significant expression is still achieved, pointing to the existence of other regulators of asense in addition to the AS-C. asense differs from the other AS-C members in its expression pattern, regulation, mutant phenotype and some DNA-binding properties.

Key words: Drosophila, neurogenesis, helix-loop-helix, proneural, neural precursor

INTRODUCTION

In Drosophila development, neurogenesis begins with the delamination of selected cells from a morphologically homogeneous sheet of ectoderm to become neural precursors (Ghysen and Dambly-Chaudière, 1989). Regardless of their future identity, all neural precursors are characterized by expression of a set of genes known as the ‘neural precursor genes’ (Vaessin et al., 1991; Bier et al., 1992; Brand et al., 1993). To understand the processes involved in neural precursor determination, it may be instructive to determine how this characteristic neural precursor-specific pattern of expression is achieved. We have investigated the regulation of one such neural precursor gene, asense (ase).

Obvious candidates for regulators of ase and other neural precursor genes are daughterless (da) and the proneural genes of the achaete-scute gene complex (AS-C: achaete (ac), scute (sc) and lethal of scute (l’sc); Ghysen and Dambly-Chaudière, 1989; Campuzano and Modolell, 1992). The expression of da is ubiquitous (H. Vaessin et al., unpublished data), while ac, sc and l’sc are expressed in subsets of the patches of ectodermal cells from which neural precursors will arise (proneural clusters), and then briefly in the neural precursors themselves after they become singled out by the process of lateral inhibition (Romani et al., 1987; Cabrera et al., 1987; Romani et al., 1989; Cubas et al., 1991; Skeath and Carroll, 1991; Martín-Bermudo et al., 1991). In the PNS, loss of function of ac or sc removes specific subsets of the stereotypic arrangement of external sense organs (García-Bellido and Santamaria, 1978; García-Bellido, 1979; Dambly-Chaudière and Ghysen, 1987). The absence of da function results in the loss of all sense organs (Caudy et al., 1988a).

The three AS-C genes encode transcription factors of the basic-helix-loop-helix (bHLH) family (Villares and Cabrera, 1987; Alonso and Cabrera, 1988; Caudy et al., 1988b; Murre et al., 1989a and b) and are known to dimerize in vitro with the product of da, also a bHLH protein. The resulting heterodimers bind to a 6 bp consensus sequence (the E-box; Murre et al., 1989a,b; Van Doren et al., 1991; Cabrera and Alonso, 1991), and AS-C/da-binding sites are present in the upstream regions of hunchback (hb) (Cabrera and Alonso, 1991) and Enhancer of split [E(spl)] genes m7 and m8 (H. Vaessin, unpublished data). The upstream region of ac itself also has such binding sites, which are required for auto- and cross-regulation by ac and sc, respectively (Van Doren et al., 1991, 1992).

ase is the fourth member of the AS-C. It too encodes a bHLH protein (Alonso and Cabrera, 1988; González et al., 1989) and appears to be important for a subset of larval sense organs (Dambly-Chaudière and Ghysen, 1987). But unlike ac, sc or l’sc, the expression of ase defines it as a
neural precursor gene (it is expressed in all neural precursors after their formation, Brand et al., 1993). We report that ase is also distinguished from the other AS-C genes by some aspects of its mutant phenotype and DNA-binding properties.

It can be postulated that the proneural genes achieve their function in early neurogenesis by activating some or all of the neural precursor group of genes. We have addressed this by identifying a regulatory element that directs the ase neural precursor pattern of expression and showing that this element contains binding sites for AS-C/da heterodimers. Removal of these sites, however, reduces but does not eliminate expression from an ase–lacZ fusion gene, suggesting that regulators other than the AS-C must also play a major role in ase activation and its neural precursor pattern.

MATERIALS AND METHODS

DNA constructs

For the genomic ase construct, a 4.8 kb BamHI fragment from phage lsc53 (Campuzano et al., 1985) was subcloned into pBluescript (pBS-T8). This was transferred to the P-element transformation vector pW8 (Klemenz et al., 1987) to give G:4.8. For the shorter rescue fragment, G:4.8 was digested with XhoI and AvrII and religated to give G:3.5. For the lacZ fusion gene, a lacZ coding region with SV40 polyadenylation signal was excised from pC4βgal (Thummel et al., 1988) as an XmaI fragment. This was filled in with Klenow enzyme and inserted into pBS-T8 from which the coding region of ase had been removed by HindIII digestion and Klenow filling-in. The resulting construct (pBaseβgal) contained the 2 kb ase promoter region and its first six amino-acids fused in frame to the lacZ coding region. The fusion gene was transferred to pW8 as an Asp718I–NorI fragment to give F:2.0. Truncation of this was performed by excising AccI–BamHI and SnaBI–BamHI fragments from pBaseβgal (the first site being in the ase promoter, the second in the lacZ coding region), adding BamHI linkers to the 5’ ends, and reinserting them into pBaseβgal in place of the BamHI promoter fragment (to give F:1.2 and F:350, respectively). The upstream fragment was isolated as a BamHI–SnaBI fragment from pBS-T8, Asp718I linkers were added, and the fragment inserted into pWZ to give H:1.4. pWZ is a P-element vector that contains a miniwhite gene and a lacZ gene bounded by an hsp70 minimal promoter and polyadenylation signal (unpublished data).

P-element transformation

P-element transformation of flies was performed as described (Spradling, 1986). The helper P-element plasmid used was pUCrΔ2-3 (Laski et al., 1986). DNA concentrations were 500 ng/μl plasmid and 200 ng/μl helper. At least three independent lines were used for each construct.

Fly stocks

Drosophila stocks were raised on standard cornmeal-yeast-agar medium at 25°C. All stocks are described in Lindsley and Zimm (1992).

Immunohistochemistry

Rabbit anti-β-galactosidase (Cappel) was used preadsorbed at 1:10,000. Anti-ase is a rabbit polyclonal antiserum against a peptide as described (Brand et al., 1993). Avidin-biotin amplification was used (Elite ABC kit, VectaLabs). Where possible, relevant stainings were performed in parallel for the same durations to allow an estimation of quantitative differences in expression.

Mutagenesis

Site-directed mutagenesis was a PCR-mediated procedure described by Hemsley et al. (1989). The substrate for mutagenesis was a 580 bp BamHI fragment from fusion gene F:560 subcloned in pBluescript (pBS-Sna). Essentially, 25 bp oligonucleotides were synthesized to the sequences flanking each E-box. PCR was performed with each pair of primers using supercoiled pBS-Sna as the template, yielding a linear product lacking the 6 bp E-box sequence. The product was treated with Klenow enzyme, gel purified, 5’ phosphorylated with polynucleotide kinase and then circularized with DNA ligase. After bacterial transformation, plasmid DNA was isolated from a number of colonies and sequenced (Sequenase, USBiochemicals) using primers to the flanking polylinker. Further rounds of mutagenesis were performed as required for double and triple mutants.

Protein synthesis

Bacterially expressed l’sc and da proteins were gifts from H. Vaessin and were fusion proteins produced by the pET3 system. sc and ase proteins were produced using the ProBond system (Invitrogen). Their reading frames were synthesized by PCR from plasmid templates and inserted into pRSET in frame with the His6 leader peptide. Growth in BL21(DE3)pLysS bacteria, induction of protein, isolation of protein by binding to a Ni2+ resin under denaturing conditions and renaturation are described in Jarman et al. (1993).

DNA binding

30 bp oligonucleotides were synthesized for the four E-boxes and complementary pairs were annealed. 5’-Terminal G residues were added to the sequence as necessary; labelling was achieved with Klenow enzyme and [32P]dCTP. The sequences are as follows:

<table>
<thead>
<tr>
<th>Primer</th>
<th>Sequence</th>
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<tr>
<td>E1 (+307 bp)</td>
<td>AGCGGGGCGC CAGTTCCTGGGGGAG</td>
</tr>
<tr>
<td>E2 (+183 bp)</td>
<td>GTCGGGAGCCTTGCTGTGGG</td>
</tr>
<tr>
<td>E3 (+45 bp)</td>
<td>GCTGAGTTGTAGCTGAGTTTCCTG</td>
</tr>
<tr>
<td>E4 (+18 bp)</td>
<td>CGACCTTGAGC CAGTGGCAGTTTGGG</td>
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Electrophoretic mobility shift assays were performed as described (Jarman et al., 1993), and generally included 0–300 ng protein and ~100 pg oligonucleotide.

RESULTS

The phenotype of ase1 and partial rescue by genomic fragments

To examine the function and regulation of ase, we first characterized its loss-of-function phenotype and the ability of genomic fragments to rescue this. Despite its expression in all neural precursors, flies lacking ase gene function show only reduced viability. Adults homozygous for the mutation ase1 (formerly known as sc1), a 17 kb deletion that is null for ase, have a reduced number of scutellar and abdominal bristles (Lindsay and Zimm, 1992; González et al., 1989).

We have evidence, however, that most of the adult phenotype is due to a perturbation of the nearby sc gene rather than the loss of ase, presumably through the loss in ase1 of part of the enhancer array that directs the expression of sc in the scutellar region and other areas (Ruiz-Gómez and Modolell, 1987). This is shown by the inability of these ase1 defects to be complemented by In(l) sc10-1 (which eliminates ac, sc but not ase function) — i.e. the affected bristles are also reduced in In(l) sc10-1/ase1 transheterozygotes (indeed, in such flies loss of scutellar and abdominal bristles...
is exacerbated) (unpublished). Nevertheless, we have identified a previously unnoticed character, a defect in the stout row of mechanosensory bristles of the wing margin, that results from lack of ase rather than perturbation of sc (Fig. 2C–E). This ase\textsuperscript{d} defect is seen neither in transheterozygotes with In(1)\textsuperscript{sc}\textsuperscript{10-1} nor in those with Df(1)\textsuperscript{sc}\textsuperscript{19} (a deletion of ac, sc, and l\textsuperscript{sc}, but not ase). Examination of the stout row in ase\textsuperscript{d} flies shows a rather variable phenotype of deformed bristles. Examples of twinned andocketless bristles, and bristleless sockets can be observed. The defect can be quite severe, with buckling of the wing blade in areas of extensive fusion of sensillum material (Fig. 2D). There may also be missing bristles, but the other defects make this difficult to determine.

To look for rescue, a 4.8 kb genomic fragment that includes the ase transcription unit and 1.6 kb from the promoter region was introduced into flies by P-element transformation (Fig. 1, construct G:4.8). We observe that the thoracic and abdominal bristle phenotype is not rescued in ase\textsuperscript{d} flies containing up to four copies of G:4.8 (five lines tested), which is consistent with this phenotype’s resulting from a perturbation of sc function. Conversely, a single copy of the G:4.8 is sufficient to rescue the wing margin defect completely (Fig. 2E, four lines tested), thus confirming that this is a function of ase. From mosaic analysis, it had been reported that the stout row bristles were among the few adult external sense organs not affected in AS-C mutants (Garcia-Bellido and Santamaria, 1978), but our results, and more recent mosaic results (M. Guo, M. B, A. P. J, and Y. N. J., unpublished), show that this is not so.

Embryos that lack ase are viable, but a specific subset of sense organs is missing (Dambly-Chaudière and Ghysen, 1987). Most consistently, an abdominal papilla, p5, is completely absent. Therefore, we scored this organ to assess the ability of the G:4.8 fragment to rescue the embryonic phenotype. Two independent transformant lines show a partial rescue of this organ (8.7% and 16% respectively in ase\textsuperscript{d} larvae with two G:4.8 copies vs. 0% and 89% detected in ase\textsuperscript{d} and wild-type larvae respectively). There may be a number of reasons for the lack of complete rescue. Expression of ase from G:4.8 may be inadequate, either because the pattern is incomplete (for example, if some regulatory elements are outside G:4.8) or the level is too low. Immunohistochemical staining of ase\textsuperscript{d} embryos containing two copies of G:4.8 with an antibody specific for ase shows a pattern of expression that appears to be similar to that of the normal gene: essentially, expression is observed in neural precursors (Fig. 2A,B). The level of expression, however, appears to be significantly lower than ase expression in wild-type embryos from parallel stainings (not shown). Given the genetic dependence of the adult phenotype of ase\textsuperscript{d}, it is also possible that the perturbation of sc may affect these larval organs.

A shorter genomic fragment that includes only 167 bp upstream of the transcription start site (Fig. 1, G:3.5) has also been tested for rescue of the adult phenotype. Expression of ase is even weaker from G:3.5 than from G:4.8 in both embryos and the imaginal discs (ectodermal primordia of adult epidermis) (not shown). Nevertheless, this low level of expression is sufficient to rescue the wing margin defect.

From the genomic rescues, we conclude that, while some of the regulatory sequences required for ase function may be absent from the two genomic fragments examined, an element directing the major pattern of expression in neural precursors has been located, and this is responsible for at least one of the functions of ase.

\textbf{ase–lacZ fusions}

To study the action of the regulatory element present in G:4.8, we constructed a fusion gene consisting of the upstream region present in this rescue fragment, including its presumed TATA box and initiation codon (González et al., 1989), fused in-frame to a lacZ reporter gene (Fig. 1, F:2.0). This includes the 455 bp 5′ untranslated region (UTR) of the ase transcription unit as well as 1.6 kb upstream of the transcription start site.

In embryos containing this fusion gene, all identifiable neural precursors express β-galactosidase as they arise (Fig. 3A–C, three independent lines tested), although this is initially rather weak. In older embryos, owing to perdurance of the β-galactosidase protein, staining is seen in the progeny of the neural precursors (Fig. 3D). In the PNS, this is particularly strong in the neuron and its sister cells. β-galactosidase expression is also seen in other places that express ase — particularly in cells of the posterior midgut rudiment from stage 11 onwards [see Campos-Ortega and Hartenstein (1985) for staging], later in the anterior midgut and in some cells of the Malpighian tubules. Neural precursor expression is also seen in the imaginal discs (Fig. 3E). Thus, apart from the perdurance of the β-galactosidase, the pattern of expression is identical to that of ase (Brand et al., 1993).

Truncations were performed to give two fusion genes with 1.2 kb and 560 bp of sequence upstream of the translation start site, respectively (Fig. 1, F:1.2 and F:560) (four...

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**Fig. 1.** A genomic map of \textit{ase} showing the rescue and fusion gene constructs. The gene is depicted with the 5′ untranslated region unhatched. The transcription and translation start sites are indicated. The four E-boxes mentioned in the text are downstream of the indicated transcription start site. Restriction sites referred to in the making of the constructs are Ac, AccI; Av, AvrII; B, BamHI; H, HindIII; S, SmaBI. The fragments used for genomic rescue are depicted above the map. The fusion gene fragments shown below were each fused in frame to a lacZ coding sequence that had an SV40 poly(A) signal. For the heterologous promoter construct, H:1.4, the upstream promoter fragment was attached to a lacZ gene including a basal hsp70 promoter.
lines tested for each). The latter is equivalent to the shorter rescue fragment, G:3.5, and is close to the minimum that can be achieved given that the presumed TATA-box and transcription start site are 480 and 455 bp upstream of the initiation codon, respectively. Both constructs appear to support an identical pattern of β-galactosidase expression to the original fusion (F:560 shown in Fig. 4A–C). The 560 bp fusion is generally weaker, with a more pronounced background. It also shows an extra pattern element consisting of pair-rule-like stripes in the ectoderm from stage 8 onwards, which could indicate the loss of an inhibitory element.

To assess the contribution of the remainder of the 2 kb promoter region excluding the 560 bp proximal fragment, we made use of a basal promoter (hsp70 TATA box) fused to a lacZ coding region. The 1.4 kb upstream portion of the 2 kb fragment was inserted into this (Fig. 1, H:1.4). Of five independent lines analysed, none showed a neural precursor pattern of β-galactosidase expression in either embryos or imaginal discs. In two lines, H:1.4 supports β-galactosidase expression in either embryos or imaginal discs. In two lines, H:1.4 supports β-galactosidase expression in a small set of late neural cells in the CNS, stomatogastric nervous system and part of the antennomaxillary complex (Fig. 4). Although we have not excluded position effects, this pattern partly corresponds to a late component of expression observed for ase (Brand et al., 1993) and may indicate that a separate component of ase regulation is present in H:1.4.

**Behaviour of the fusion gene in mutant backgrounds**

As a step in identifying genes that regulate ase through the identified promoter element, we have recorded the effect of mutation of the proneural genes on the neural precursor expression pattern of the 2 kb ase–lacZ fusion. In embryos carrying the deficiency Df(2R)daKX136, PNS precursors appear to be absent although initially the neuroblasts of the CNS segregate normally (Ghysen and O’Kane, 1989; Bodmer et al., 1989; Brand and Campos-Ortega, unpublished data; Vaessin et al., unpublished data). We observe an overall reduction in the expression of the fusion gene in the segregating neuroblasts of da mutant embryos (Fig. 5A,C), although this is not as pronounced as the reduction seen for the endogenous gene (Brand et al., 1993). Patchy, weak staining is also seen in the epidermis, particularly in the areas that would normally give rise to PNS precursors (Fig. 5A,B).

The effect of removing the genes of the AS-C was analysed in the deficiency Df(1)scB57, which lacks all four genes of the complex. It results in the absence of much of the larval PNS, although the chordotonal organs and some multiple dendrite neurons are unaffected (Dambly-Chaudière and Ghysen, 1987). The CNS is also strongly affected later, but early on up to 75% of the neuroblasts segregate normally (Jiménez and Campos-Ortega, 1990). With the fusion gene in this background, the remaining neural precursors of the PNS express β-galactosidase as before. Those CNS neuroblasts that segregate also express β-galactosidase, but the onset of expression is significantly delayed, often until late in stage 10 (Fig. 5D). Normally, the neuroblasts express β-galactosidase before it is detectable in the PNS precursors. In mutant embryos, however, expression is seen in one of the two earliest arising PNS precursors (the P cell, which gives rise to the abdominal lateral
Regulation and function of a sense chordotonal organ, lch5, Ghysen and O’Kane, 1989) before it is seen in the neuroblasts. Therefore, although the remaining neuroblasts in Df(1)sc B57 embryos segregate at the correct time, it appears that they do not activate the fusion gene normally.

In Df(1)sc B57 embryos, the other early PNS precursor, the A cell (see Fig. 3), is reported to be absent, consistent with its being the precursor of an external sense organ that is dependent on AS-C gene function (Ghysen and O’Kane, 1989). Curiously, we observe in Df(1)sc B57 embryos that the fusion gene is sometimes transiently activated in a large subepidermal cell in the position expected for this neural precursor (Fig. 5D) [11% of scored segments (n=147)]. The cell disappears soon after. We note that the A cell gives rise to a partially ase-dependent sense organ (Dambly-Chaudière and Ghysen, 1987; Dambly-Chaudière et al., 1992) (see Discussion).

In the deficiency Df(1)sc B19, all the members of the AS-C are deleted except ase. Its embryonic phenotype differs from Df(1)sc B57 in a less severe reduction of the CNS and the additional presence of certain PNS elements that are partially ase-dependent. In the PNS, at late stages we now see high levels of fusion gene expression in the ase-dependent organs that form in addition to those elements seen in Df(1)sc B57 embryos (Fig. 5G,H). In the neuroblasts, the delay in expression of the fusion gene is less pronounced.

Fig. 3. 2 kb of the ase upstream sequence can drive expression of β-galactosidase in a neural precursor pattern. (A–D) Wild-type embryos containing the 2 kb ase-lacZ fusion gene (F:2.0) were stained with an antibody to β-galactosidase. (A) Lateral view of a stage 10 embryo. Neuroblasts are seen in cross section below the epidermis. Staining in the posterior midgut anlage occurs slightly later than this. (B) Stage 11 embryo, lateral view showing the earliest PNS precursors. These correspond to the A and P cells as seen in enhancer trap line A37 (Ghysen and O’Kane, 1998), which give rise to an external sense organ (des2) and a chordotonal organ (lch5) respectively (Dambly-Chaudière et al., 1992; Ghysen and O’Kane, 1989). The expression in the neuroblasts and ganglion mother cells of the developing CNS is bracketed. (C) The A and P precursors magnified. At this stage, each appears to consist of a pair of cells. (D) Lateral view of a stage 16 embryo showing perdurance in the PNS. Staining is most apparent in the neurons and inner support cells. (E) β-galactosidase staining of a wing disc of a wandering third instar larva of the same line, with identified precursors labelled [see Huang et al. (1991) for nomenclature]. The onset of staining appears to be somewhat delayed relative to ase, possibly reflecting a slower rate of synthesis of β-galactosidase and the cytoplasmic nature of the protein.
than for Df(1)sc^B57 embryos, possibly due to regulation by endogenous ase despite its delayed activation (Fig. 5F).

In summary, the reduced expression in Df(2)da^KX136 neuroblasts and the delayed expression in Df(1)sc^B57 neuroblasts suggests that activation of the F:2.0 fusion gene is at least partly due, directly or indirectly, to da and the genes of the AS-C, including ase itself. The remaining expression in these mutants, however, means that additional factors must also play a role.

**AS-C/da-binding sites in the 560 bp fragment**

To determine whether the neural precursor expression pattern supported by the fusion gene can be attributed to direct regulation by the binding of proneural gene products, we examined the sequence of the 560 bp minimal ase fragment from fusion gene F:560 for potential binding sites (González et al., 1989). bHLH proteins bind to variants of a consensus sequence known as the E-box (CANNTG) (Murre et al., 1989b), and four such E-boxes are present in the ase sequence, each in the 5′UTR. To look for binding, oligonucleotides were synthesized (see Materials and Methods) and electrophoretic mobility shift assays were performed using bacterially synthesized proteins sc, l’sc, and da. Two of the sites, E1 (CAGCTG) and particularly E4 (CAGGTG), bind l’sc/da hetero-oligomers (presumably heterodimers) strongly (Fig. 6A). The E-box sequences at these sites match those previously identified as binding sites for AS-C/da heterodimers, all of which have the consensus CAG^f/G/TG, (Van Doren et al., 1991; Cabrera and Alonso, 1991; H. Vaessin, unpublished). The other two potential sites bind l’sc/da heterodimers only weakly (E3; CAGATG) or extremely weakly (E2; CAAATG), correlating with their decreasing similarity to the consensus. Heterodimers of sc/da bind in a similar fashion (Fig. 6B). In agreement with previous reports (Cabrera and Alonso, 1991; Van Doren et al., 1991), we find that AS-C homodimers bind very poorly, the strongest detected being a very weak binding of l’sc/l’sc to E1. The binding of da/da homodimers is also poor.

We have also examined the ability of ase itself to bind to the E-box sequences in its 5′ UTR (Fig. 6C). Bacterially expressed ase protein binds as a heterodimer with da in a manner similar to l’sc and sc: ase/da binds well to sites E1 and E4, poorly to E3, and minimally to E2. Unlike sc, l’sc or da, we also observe the binding of ase/ase homodimers to site E1, and occasionally to E4. At equivalent or higher protein inputs, l’sc and sc barely show binding as homodimers. Thus, the binding properties of ase appear to differ from those of the other AS-C genes.

**In vitro mutagenesis of the AS-C/da-binding sites**

On the evidence of the in vitro binding, we looked for an effect of deleting the E-boxes on the regulation of the fusion gene. Deletions of 6 bp were made to the 560 bp ase–lacZ fusion gene and flies were transformed. Deletion of single sites E1, E3 or E4 was found to have no detectable effect on expression in either embryos or discs (E2 was not done). Concluding that this may be due to redundancy between the binding sites, we then performed a double deletion of both strong sites (E1 and E4). With this construct (5 lines examined), neural precursor expression was still apparent, but the level of expression was discernably lower than the unmutated construct (Fig. 7). Also, we now observe much greater patchy expression in the ectoderm as though there is some deregulation of the fusion gene. Embryos containing a triple deletion of all three sites that showed appreciable binding (E1, E3 and E4) were indistinguishable from those with the doubly deleted construct (not shown).
Fig. 5. Expression of the 2 kb ase–lacZ fusion gene in proneural mutants. (A–C) Expression in Df(2R)da2/CX embryos. (A) Stage 10, showing expression in ectodermal cells as well as in neuroblasts. (B) Stage 11 PNS, showing residual patchy staining in the ectoderm (bracket). (C) At stage 16, some staining is seen in the remnant CNS (arrows), mostly corresponding to the late phase of ase expression, which is da-independent. (D,E) Expression in Df(1)Xc387 embryos. (D) Staining in the neuroblasts (bracket) is delayed until after staining is seen in the first PNS precursor (P cell, arrowhead) in a stage 11 embryo (cf. Fig. 3B). Note that staining is seen in an additional cell (open arrow), which may correspond to the aborted formation of the A precursor. (E) At stage 16, β-galactosidase is seen in the remaining PNS (chordotonal organs and multiple dendritic neurons) and in the remnant of the CNS. (F–H) Expression in Df(1)Xc19. (F) The delay in neuroblast expression is less apparent, as seen in ventro-lateral view of a stage 10 embryo. The P precursor of Ich5 is indicated by an arrow. Staining of the neuroblasts begins rather unevenly. (G) At stage 16, expression is additionally seen in those PNS elements that now form due to the ase function (external sense organs). (H) Magnified view of the lateral PNS cluster of three abdominal segments of a Df(1)Xc19 late embryo, showing perturbation of fusion gene expression in PNS elements with a variety of identities and origins. Indicated are the four cells of each chordotonal organ in Ich5 (cap, c; sheath, s; neuron, n; and ligament, l), the extra attachment cells of Ich5 (a), part of v.ch1, the dorsal bipolar dendritic neuron (dbd), and the ase-dependent external sense organ (lesB). The expression in the midgut primordium is abolished in Df(1)Xc387, Df(1)Xc19 and Df(2R)da2/CX backgrounds (out of focus).
DISCUSSION

Despite their different identities and origins, all neural precursors express a common set of products derived from the neural precursor genes (Vaessin et al., 1991; Bier et al., 1992). As a step in understanding how this is achieved, we have examined the regulation of \( ase \) as a representative of this group of genes. To this end, we have located the minimal \( ase \) regulatory region that is able to support its neural precursor pattern of expression. The transcription factors of the proneural genes (AS-C and da) are prime candidates for neural precursor gene activation and we have established that the \( ase \) regulatory element contains AS-C/da-binding sites. Since the proteins of the AS-C are expressed in proneural clusters, this raises the question of how \( ase \) expression is confined to the neural precursor. We discuss the possibilities for this regulation. Furthermore, in line with its differing expression pattern, we have also found other distinguishing features between \( ase \) and the other AS-C genes: we have characterized an \( ase \) function that suggests a role later in neurogenesis, after neural precursor formation.

The function of \( ase \) in the neural precursor

The AS-C genes are thought to be involved in the earliest stages of neural precursor formation. \( ae, sc \) and \( l’sc \) have an
expression pattern (in proneural clusters) and mutant phenotype (absence of sense organs and their precursors) consistent with this. Given the later expression of ase, one may ask whether this gene has a later function in neural precursors. However, the analysis of embryonic phenotypes (Ghysen and Dambly-Chaudière, 1987; Jiménez et al., 1990), the similar effects of ectopic expression of sc, l’sc or ase (Rodríguez et al., 1990; Brand et al., 1993) and the DNA-binding characteristics (Cabrera and Alonso, 1991; Van Doren et al., 1991; this report) all suggest a high degree of interchangeability between the products of the AS-C, including ase. Taken with its later expression pattern, one possible function of ase is to reinforce the effect of the other AS-C products in determining the neural precursor state.

We have obtained some observations, however, that suggest a later role for ase in some neural precursors that is more distinct than a simple boosting of proneural gene function. In flies lacking ase, we have identified that the stout row of bristles on the wing margin shows such morphological defects as stunting, fusing and twinning, as opposed to a simple absence of sense organs. Introduction of genomic ase fragments can efficiently rescue the wing-margin defect. This suggests a role for ase in the later development of the neural precursors of the stout row or their descendents after their formation. The reported misrouting of axons in the optic lobe of ase/ flies may also point to a later function (González et al., 1989).

We have a similar observation concerning ase function in the embryo. Certain external sense organs depend on AS-C function, but can form even when ase is the only AS-C gene present (Dambly-Chaudière and Ghysen, 1987). Although this suggests an early proneural function for ase, we have found that, in the case of one such partially ase-dependent sense organ, its precursor (the A cell) appears occasionally to delaminate in the absence of any AS-C gene function, implying that here too the requirement for ase is in precursor survival/development rather than in formation. It also suggests that unidentified (proneural) factors are responsible for the initial formation of this precursor.

Role of proneural genes in the neural precursor regulation of ase

Our analysis shows that 560 bp of the ase locus can direct a neural precursor pattern from a lacZ reporter gene — a portion that consists of the 5′ UTR of the transcription unit and the upstream TATA sequence. This segment contains multiple binding sites for AS-C/da heterodimers, suggesting that neural precursor genes are directly activated by the bHLH products of the proneural genes of the AS-C complex and da. Nevertheless, removal of these sites lowers but does not abolish lacZ expression in neural precursors. In contrast, Van Doren et al. (1992) have shown that mutation of similar AS-C/da-binding sites in an ac autoregulatory element leads to the complete loss of the proneural cluster expression that this ac–lacZ fusion gene normally exhibits (Martínez and Modolell, 1991). This difference may help to explain the different expression patterns of the two genes despite their shared possession of AS-C/da-binding sites; the proneural pattern of ac relies strongly on its AS-C/da-binding sites, while the neural precursor pattern of ase requires additional regulatory inputs.

As evident from the continued expression of the ase–lacZ fusion in mutants of AS-C and da, it is likely that the additional factors that regulate ase are also responsible for the remaining neural precursor formation seen in these mutants. Many other potential transcription factors are expressed in neural precursors and could be involved in neural precursor gene activation, including a number of zinc-finger-containing proteins, such as hb (Tautz et al., 1987; Jiménez and Campos-Ortega, 1990), Krüppel (Kr, Gaul et al., 1987) and scratch (E. Bier, unpublished) (see Cabrera, 1992). The stronger effect of the da mutant on fusion gene expression also suggests that da may have other unidentified bHLH partners, both in the CNS (responsible for the remaining neuroblast formation) and in the PNS (responsible, for example, for chordotonal organ formation). Indeed, we have recently isolated a candidate proneural gene for chordotonal organ formation (Jarman et al., 1993). The bHLH product of this gene, atonal, also binds to the E-boxes in the ase 5′-UTR as a heterodimer with da.

There may also be negative influences that prevent activation of ase, but not ac, in the proneural clusters by AS-C/da proteins. A number of observations indicate this, in particular the abnormal ectodermal expression that is seen when the AS-C/da-binding sites are deleted. It is possible that the AS-C/da-binding sites are adjacent to, or overlap with, binding sites for negative regulators. Close proximity of positive and negative sites is a common means of sharply defining expression patterns, as seen in the studies of even-skipped (Small et al., 1991), Kr (Hoch et al., 1992), Ultra-bithorax (Müller and Bienz, 1992), and rhomboid (Ip et al., 1992). A number of the neurogenic genes involved in lateral inhibition within the proneural clusters encode potential transcription factors [E[spl], neuralized], and these would be candidate inhibitors of ase within the clusters.

ase as a transcription factor

As would be predicted from their similar bHLH domains, the DNA-binding properties of ase protein are very similar to those of ac, sc and l’sc. For the four E-boxes in the ase promoter, the binding of ase/da heterodimers occurs in a similar fashion to that of sc/da and l’sc/da; that is, binding is strongest to a consensus of CAGTG. Nevertheless, the upstream sequence is not simply an autoregulatory element — the pattern and level of expression from the 2 kb ase–lacZ fusion gene is essentially unchanged in ase/ embryos (not shown). An apparent difference in binding properties, however, is that, unlike ac, sc or l’sc, ase can also bind well as a homodimer. It is known that a truncation allows the bHLH protein E12/47 to bind as a homodimer (Sun and Baltimore, 1991). Also, the removal of the C terminus from l’sc appears to increase homodimerization as measured by immunoprecipitation (Cabrera and Alonso, 1991). Interestingly, this C-terminal sequence is conserved in ac, sc and l’sc, but not in ase (Villares and Cabrera, 1987; Alonso and Cabrera, 1988; González et al., 1989). It remains to be determined whether the ability of ase to bind to DNA as a homodimer reflects some aspect of its function, such as a potential later role in the developing neural precursors or their progeny.

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